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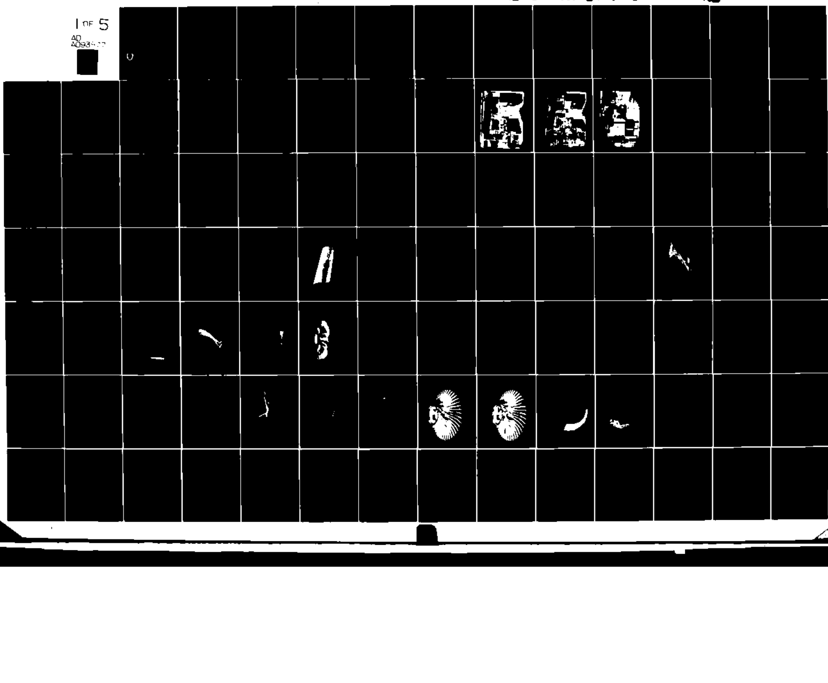

USAAVRADCOM TR 80-F-1 LEVEL (12)

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MANUFACTURING METHODS AND TECHNOLOGY
(MANTECH) PROGRAM

AD A093877

T700 BLISK AND IMPELLER MANUFACTURING PROCESS DEVELOPMENT PROGRAM

W.A. HUNTER
G.A. GRIMMER
General Electric Aircraft Engine Group
Lynn, Massachusetts

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JAN 16 1981

November 1979

FINAL REPORT

Contract No. DAAJ01-75-C-0844

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| Impeller | Five-Axis Milling | |
| Axial Compressor | | |

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)


Highly automated processes were developed to machine and control the quality of airfoils on the blisks and impeller which are the principal rotating components of the compressor for the T700-GE-700 engine, which powers advanced military helicopters. This development was carried out under a Manufacturing Methods and Technology contract awarded by the Army Aviation System command, which later became the Army Aviation Research and Development Command (AVRADCOM), to the Aircraft Engines Business Group of the General Electric


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20. ABSTRACT - Continued

Company in Lynn, Massachusetts. Processes which were previously available, and which were used to produce airfoils for development engines, were too costly and too dependent on manuals skill to meet volume production requirements.

Five-axis precision contour milling was developed to machine the airfoils of the five axial flow blisk stages and the impeller, all of which are integral with their supporting disk. A new milling machine was designed for this process, which machines four identical parts simultaneously. This machine is directed by advanced computer numerical control. The programs which supply positioning information to this control for machining blisk airfoils were developed with APT; and special programming techniques that were devised for these programs. The programs for machining impeller airfoils were developed with HECTRAN, which is a proprietary processor for impeller machining programs. New and advanced features were devised for HECTRAN to meet the objectives of this development program. A unique method was used for monitoring the milling process to control airfoil thickness within close tolerances.

Abrasive flow machining was developed to produce the final surface texture on blisk and impeller airfoils and to produce the final critical contours of airfoil leading and trailing edges. This is the first application of abrasive flow machine for finishing axial flow airfoils.

Precision tracing was developed to measure airfoil characteristics, including contour, thickness, warp angle, and true position of sections.

All of these processes were transitioned into volume production easily and quickly, in a new facility equipped with new machines which meet both process and production requirements. They have made possible manufacturing costs which are 60% less than costs attainable with previously used processes. As a result, they will provide savings of over $60 million, which will give a return of more than 40 to 1 on the Army's investment of $1.4 in this Manufacturing Methods and Technology (MMT) program.

In addition, these processes have significantly improved the quality of airfoils, which has resulted in an important improvement in engine performance. And they have made it possible to link computer aided airfoil design, with computer aided airfoil manufacture, so that the first airfoils of a new design can be produced much sooner after design data becomes available than was previously possible.

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PREFACE

A number of organizations and people made important contributions to this development program.

The overall program was made possible by the U.S. Army Aviation Research and Development Command in St. Louis, Missouri. In addition, this organization assisted in the resolution of special needs as the program was executed. Individuals who were most directly concerned are Mr. Fred Reed and Mr. Robert Vollmer.

The New England Machine and Tool Company, Berlin, Connecticut, designed and built the development milling machine. This machine, with its great precision and its unique five-axis and four-spindle capability was vital to this program. Mr. Paul Campbell, President of the Company, personally directed this work.

A major contribution to the development of numerical control programs for the impeller was made by Mr. Lee B. Stripling who is President of Intratec, Inc., Neptune Beach, Florida. He is the developer of HECTRAN, which is the computer processor used to program the impellers.

A major contribution was made to the development of abrasive flow machining for the blisks and the impellers by Dynetics Corp., Woburn, Massachusetts. Mr. John Stackhouse, who is President of the Company, worked closely with General Electric engineers on this development.

The unique airfoil tracing machine used during the development program was designed and built by Centerline Precision Manufacturing, Warwick, Rhode Island. Its flexibility and accuracy were essential to the success of the program.

Special, highly precise milling cutters were provided by the P.O. McIntire Company, Cleveland, Ohio, on very short delivery schedules, which were essential to the program.

Tests of free-abrasive machining processes were made in the laboratories of the following companies: Almco Queen Products Division, Albert Lea, Minnesota and Harper Buffing Machine Co., East Hartford, Ct. This work was of important help in determining the capabilities of free-abrasive machining for producing the final surface texture on blisk and impeller airfoils.

Cutting force data, which was essential to the development of rough contour milling parameters, was obtained through tests and analyses made under the direction of Professor Nathan H. Cook of the Massachusetts Institute of Technology, Cambridge, Massachusetts.

Ace Industries, Santa Fe, California which produced blisks and impellers for all of the early T700 engines, starting several years before this development program was undertaken, provided information on their experience which contributed to the success of this program.

The Industrial Control Department of the General Electric Company, Charlottesville, Virginia, designed and built the numerical control for the development milling machine.

TABLE OF CONTENTS

TABLE OF CONTENTS - Continued

TABLE OF CONTENTS - Continued

## SUMMARY OF BLISK AND IMPELLER AIRFOIL MANUFACTURING PROGRAM

### PURPOSE

The purpose of this program was to develop an advanced manufacturing system for machining airfoils on the blisks and impeller which are the rotating components of the compressor for the General Electric T700-GE-700 turboshaft engine. This engine is a new, light weight, compact, high performance engine which powers modern military helicopters.

### NEED

The airfoils on blisks and impellers are machined on the disks or hubs which support them. Currently available airfoil volume production processes such as forging cannot be used to produce blisk and impeller airfoils because the existing processes are only suitable for making separate airfoils which are assembled to their disks after the airfoils are machined.

Blisk and impeller airfoils for development and early production T700-GE-700 engines were machined with manually controlled tracer milling, after which manual abrasive machining was used to generate final contours and surface texture. These processes are suited to low volume production but are not suitable for high volume production. Manufacturing costs with them are high because they are labor intensive. Also, airfoil quality is heavily dependent on manual skill. Furthermore, the time needed to introduce airfoil design improvements was too long.

Available manufacturing capacity was inadequate to satisfy total production requirements and capacity could not be readily increased because of the large amount of skilled labor which is necessary to produce airfoils with these manual processes.

Therefore, a new system was needed to manufacture blisk and impeller airfoils in volume production. It had to be developed quickly for incorporation in a new manufacturing facility which was to be established to meet total production requirements. Processes used in the system had to be highly automated to meet cost requirements, to make quality essentially independent of manual skill, to allow rapid introduction of design improvements, and to allow sharp increases in production rates.

There are five axial stages in the T700 engine compressor. The rotating components for these stages consist of four blisks. There is a Stage 1 blisk, a Stage 2 blisk, a Stage 3 and 4 blisk, and a Stage 5 blisk. There is also one centrifugal stage and the rotating component for this is an impeller. These components are shown in Figure 1 (pg 5). The outside diameter of the Stage 1 blisk is approximately 7.7 inches and the outside diameter of the impeller is approximately 9.4 inches.

### PROGRAM DESCRIPTION

A Manufacturing Methods and Technology contract was awarded by the U.S. Army Aviation Research and Development Command to develop processes which could be combined into a new system for manufacturing blisk and impeller airfoils. Specific schedule and manufacturing cost goals were established for this development program.

PROGRAM DESCRIPTION - Continued

The contract specified that five-axis numerically-controlled contour milling would be used in the new system and the contract provided for the design and construction of a prototype milling machine. The contract also called for the investigation of ways to produce numerical control programs for the milling machine and for the development of these programs.

The contract also called for investigation of processes for rough machining of airfoils, processes for producing the final texture of airfoil surfaces, and processes for controlling airfoil quality. Furthermore, the contract provided for the selection and development of all of the processes required for the complete system, as well as the development of specifications for process equipment.

Finally, the contract required that the capability of the system be fully demonstrated by producing airfoils on complete blisks and impellers and subjecting them to approval tests in the laboratory and in engines.

Process Development work began in June 1975 and was completed in June 1979. Production of each component started as soon as development for a component was completed.

## System Description

Airfoils are rough contour milled on a numerically-controlled (NC) machine, and are immediately finish contour-milled to final dimensions on the same machine, excepting leading and trailing edge dimensions. The airfoils are then finished with abrasive flow machining to obtain final edge dimensions and final surface texture. Next, airfoil dimensions are measured by instantaneous comparison with design dimensions, except for leading and trailing edge contours. Finally, leading and trailing edge contours are examined optically and surface roughness is measured with a profilometer.

The only significant manual operations are: loading parts into machines and unloading them; loading cutters into the milling machine and unloading them; inspecting edge contours; determining surface roughness; selective improvement of blisk platform surfaces; and removal of burrs from impeller airfoil tips after contouring in a lathe. Work is being done to eliminate the last two operations.

## Technology

The airfoil milling machine has four spindles, so that four identical components are milled simultaneously. It is capable of milling airfoils on all of the blisks and the impeller. The machine has five numerically-controlled axes. Four are used for blisk airfoil milling and the fifth axis is used for test block milling which is done to control airfoil thickness. All five axes are used for impeller airfoil milling. The machine was designed specifically for this blisk and impeller airfoil manufacturing program.

PROGRAM DESCRIPTION - Continued

The milling machine is directed by a computer numerical control adapted specifically for this program. Digital instructions are supplied to this control from numerical control programs which are stored in a central computer. The computer supplies program instructions to a number of machines which are all operating simultaneously and while different airfoils are being milled by each machine. Program instructions can also be supplied at a slower rate from punched tape through a tape reader, which results in increased machining time.

Separate numerical control programs were developed for contour milling the five different blisk and three different impeller airfoil designs. Airfoil programs were produced with large computers. APT was used for producing the blisk airfoil programs and HECTRAN for the impeller airfoil programs.

Unique programming techniques were developed for APT to apply it to blisk airfoil programming. A new and improved version of HECTRAN was developed for impeller programming. As a result of this work it is now possible to produce milling programs for new airfoil designs directly from computer stored information which is generated by design engineers as a normal part of the design process.

Contour milling methods and parameters were developed specifically for producing blisk and impeller airfoils that have design requirements which make them unusually difficult to manufacture. Methods and parameters that were developed include cutting paths, cutter geometry, cutting speeds, and feed rates. A unique method for controlling the influence of the milling process on airfoil thickness was developed. Test blocks are milled to geometry that can be easily measured and the measurements are used to control the varying effect on airfoil thickness of cutter manufactured geometry, cutter wear, cutter deflection, and cutter runout.

Abrasive flow machining was applied for the first time to finish axial flow airfoils, including blisk airfoils. Its applications to finishing of impeller airfoils was one of the first of this kind that was successful. New fixturing concepts were developed to apply this process, as well as unique parameters including processing pressure and abrasive media characteristics.

The precision with which the numerical control programs devine airfoil design geometry, the high accuracy of the numerically controlled milling machine over a wide range of feed reates, operating speeds, and operating temperatures, and the excellent repeatability of abrasive flow machining, make it possible to produce airfoils that conform closely to design requirements.

Unique airfoil tracing equipment was developed for use during this program to measure airfoil geometry. Airfoil sections are automatically traced. The traced information is automatically compared with design nominals and limits, and displayed instantaneously. In addition, specifications were prepared for production inspection equipment, including specificatins for a numerically controlled coordinate measuring machine which will have unusual capability for application to new airfoil designs.

PROGRAM DESCRIPTION - Continued

Leading and trailing edge contours are inspected with light sectioning equipment which provides an image of the edge contour in relation to a nominal contour and limits, for visual evaluation.

Results

All of the objectives for the development program were accomplished. The most significant results which were achieved are:

1. Designed a four-spindle, five-axis, computer numerically-controlled milling machine suitable for producing airfoils on blisks and impellers, and capable of machining four parts at a time.

2. Developed complete airfoil milling capability including numerical-control programs, machining parameters, tools, and fixtures.

3. Developed automatic airfoil finishing by abrasive flow machining.

4. Developed techniques for precise measurement of airfoil contours.

5. Successfully completed approval tests, including laboratory frequency and fatigue tests, and engine tests.

6. Successfully transitioned all developments into volume production.

7. Obtained manufacturing cost reductions which will result in savings to the Department of Defense of more than $60 million for the number of engines now planned, giving a return of more than 40 to 1 on their $1.4 million investment in this Manufacturing Methods and Technology program.

8. Developed the basis for applying Computer Aided Design and Computer Aided Manufacturing (CAD/CAM) techniques to future airfoil designs.

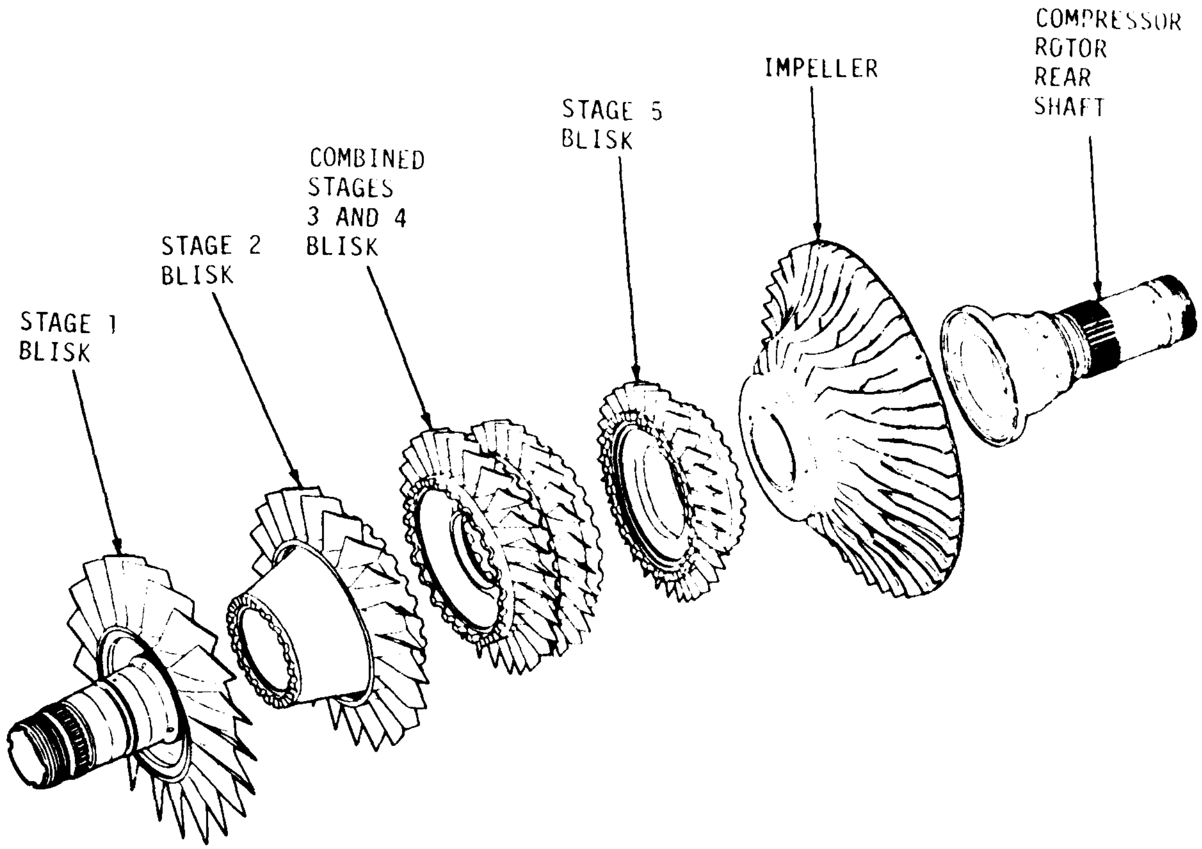



Figure 1. Blisks and Impeller for General Electric T700 Engine Compressor

NUMERICALLY-CONTROLLED
CONTOUR MILLING MACHINE

## NUMERICALLY-CONTROLLED CONTOUR MILLING MACHINE

### MILLING MACHINE DESCRIPTION

A numerically controlled 5-axis milling machine was designed and built specifically to meet the requirements of this development program. It was equipped with 4 spindles to allow milling four identical parts simultaneously. The design of this development machine was based upon a General Electric specification prepared for this development program.

Competitive quotations were solicited from eight machine tool manufacturers. Of these, only three responded to the solicitation. The New England Machine and Tool Company was selected on the basis of their technical proposal and cost.

Figures 2-4 (pgs 14-16) show various views of the development milling machine. The five axes are defined in Figures 5-8 (pgs 17-20).

During negotiations with New England Machine, the possibiity of incorporating a cutter load monitoring system, with full adaptive control, was investigated. The purpose of such a system is to obtain maximum metal removal rate without cutter breakage or spindle motor overload. A search for available systems was made. As a result, the Macotech Corporation was requested to explore the possibility of incorporating its adaptive control system into the milling machine. This system senses the radial forces applied to an end milling cutter and the motor horsepower required to drive the machine spindle to which the cutter is attached. This system regulates the feed rate at the highest rate permitted by maximum allowable cutter forces or spindle motor load. Following a review of the require- ments, it was concluded that this system would not be suitable for this application because of the relatively low cutter forces and cutter power anticipated with cutters 3/16 to 5/16 inch in diameter, which is the size range used in this program. No other suitable system was found. Accordingly, it was decided to utilize a sensitive spindle load meter for each spindle. This allowed observing relative spindle motor loads under all cutting conditions.

### NUMERICAL CONTROL

An analysis of the requirements of blisk milling revealed that a considerable amount of control data would be needed for each machining operation and the rate at which data must be presented to the machine would be quite high. It was expected that a number of reels of punched tape would be required per blisk. In addition, since tape readers are limited to 300 characters/second, it was anticipated that the milling machine operation could be paced by the tape reader if buffer storage was not adequate.

The essential requirements of the numerical control (NC) system are listed in Table 1 (pg 8). Various possibilities were evaluated in the search for a system that would satisfy these requirements. These included the following NC systems:

1. A standard General Electric Mark Century 1050 Computer Numerical Control (CNC) with dual tape readers with automatic switching and rewind.

2. The above with special additional buffer storage.

NUMERICAL CONTROL - Continued

3. The standard General Electric Mark Century 1050 CNC Unit with a single tape reader and a GECON Computer Control with a disk storage unit.

4. The General Electric Mark Century 550 Mc.

5. The General Electric Mark Century 7585.

TABLE 1
SIGNIFICANT NUMERICAL CONTROL FEATURES

1. Five simultaneous axes.
2. Microcomputer type control.
3. Two 300-cps readers with reels.
4. Expandable buffer storage.
5. On-machine edit capability
6. Alpha numeric 256-character readout.
7. Sequence readout.
8. Manual tape search.
9. Manual data input (MDI).
10. Manual feed override.
11. Incremental programming.
12. Block delete.
13. Auto,semi,single, and manual modes.
14. Dry cycle.
15. Auto retract.
16. Manual feed hold.
17. Tool length offsets.
18. Test circuits.
19. Reversal error compensation.
20. 0.001 inch resolution.
21. Inch data input.
22. EIA tape standard.
23. Auto tape rewind during cycle.
24. Automatic reader transfer.
25. Error diagnostics.
26. Leading and trailing zero suppression.
27. Memory protection.
28. Lead screw compensation.
29. Solid state servo drive system.

General Electric control systems were selected for evaluation because the Aircraft Engine Group's experience is based on General Electric Mark Century controls.

Item Nos. 1 and 2 (pg 7) were combined to provide the best NC technology available at the initiation of this Program. Thus, the General Electric Mark Century 1050 CNC Unit, with special additional buffer storage of up to 128 blocks of information, satisfies all of the requirements listed in Table 1. It includes two 300-characters/sec tape readers and a large memory capability (40,000 bytes).

Figures 2-3 (pgs 14-15) include views of the General Electric Mark Century 1050 CNC unit furnished for the 5-axis and 14-spindle development milling machine used in this Program.

## INITIAL CHECKOUT OF DEVELOPMENT MILLING MACHINE

Upon completion of the final mechanical assembly of the development milling machine at the New England Machine and Tool Company, the electrical interface with the General Electric CNC Unit was completed and checkout of the CNC control was performed in accordance with the machine test plan. Checkout tests involved operation under tape control using Stage 1 blisk contour milling NC programs and measurements of positioning accuracy with a laser interferometer measuring system.

INITIAL CHECKOUT OF DEVELOPMENT MILLING MACHINE - Continued

The following adjustments and changes were made to the machine and control system during checkout tests:

1. Adjustment of spindle motors and spindle bearings.
2. Correction of rotary axis backlash.
3. Addition of a B-axis zeroing switch.
4. Addition of automatic feed-hold control when spindle motors lose power.
5. Final balancing of servo systems in all axes.

Problems were experienced with positioning accuracy which relate to the unusually high precision requirements in the machine specification. A considerable amount of effort was expended in improving accuracy; including replacement of the Y-axis ball nut and lead screw. Following adjustments to obtain usable accuracy, to avoid delay in the development program, the machine was shipped to the General Electric Aircraft Engine Group in Lynn, Mass., even though some specification requirements were not met.

OPERATING PROBLEMS

Spindle Drive Systems

Several failures occurred with the spindle drive systems while the macine was being used for development work. The manufacturer of the systems determined that design changes were needed and installed new systems, including new motors and drive controls. Operation was satisfactory after these changes were completed except that maximum spindle speed required by the specification could not be attained.

To determine spindle motor load, tests were run over a range of cutting conditions. Results are given in Table 2 (pg 10). Maximum motor load was found to be well within the motor rating.

Changes in Alignment Between Spindles and Tables

Surface temperature measurements on the front surface of the machine member that supports the spindles and their drive motors showed that relatively large increases occurred during operation at the higher spindle speeds used for blisk platform milling. Since the temperature changes appeared to be great enough to possibly cause alignment changes between spindles and rotary tables, tests were made to investigate this possibility before attempting four spindle milling trials with the development machine.

TABLE 2
SPINDLE MOTOR HORSEPOWER FOR NEW ENGLAND FIVE AXIS
NC DEVELOPMENT MILLING MACHINE OPERATING UNDER VARIOUS CUTTING CONDITIONS

| Representative Operating Conditions | Spindle Speed (rpm) | Motor Speed (rpm) | Drive Pulley Ratio | Motor Power Not Cutting (hp) | Motor Power Cutting (hp) | Cutting Conditions | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Cutter | Feed Rate (in/min) | Cut Width (mils) |
| Rough Milling | 800 | 300 | 1.125 | 0.1 | - | 5/16 in dia. 6 flutes | - | - |
| | 1000 | 1422 | 1.125 | 0.5 | 0.9 | | 2.4 | 120 |
| | 2400 | 2133 | 1.125 | 0.8 | 1.3 | | 3.6 | 120 |
| | 4000 | 1212 | 3.3 | 0.6 | 1.5 | | 6.0 | 120 |
| Airfoil Finish Contour Milling | 3000 | 2667 | 1.125 | 1.1 | 1.2 | 5/16 in dia. 12 flutes | 15.0 | 10 |
| | 4500 | 1364 | 3.3 | 0.67 | 0.7 | | 24.0 | 10 |
| | 6000 | 1818 | 3.3 | 1.03 | 1.04 | | 30.0 | 10 |
| Platform Finish Contour Milling | 9000 | 2727 | 3.3 | 2.4 | - | 0.100 in to 0.125 dia. 12 flutes | 15 | 10 |
| | 11000 | 3333 | 3.3 | 3.3 | - | | 30 | 10 |

Note: Cutting conditions for platform finish contour milling are shown for reference only and were used in tests.

OPERATING PROBLEMS - Continued

Test procedures are described in Figures 5-8 (pgs 17-20). Test results for the relatively high spindle speed and the feed rate used for platform finish contour milling are shown in Table 3 (pg 12) and Figure 9 (pg 21). Results for the relatively low spindle speed and the feed rate used for airfoil finish contour milling are shown in Figure 10 (pg 22). Although the machine was not milling while it was operated for this investigation, alignment change results obtained should not have been significantly different from those which would have been obtained while milling. This assumption is based on the fact that spindle motor horsepower is increased insignificantly when finish contour milling; nearly all motor horsepower is consumed in driving the spindle.

Results show that alignment changes as great s 4 mils in the X-axis, 3 mils in the Y-axis, and 4 mils in the Z-axis take place when the machine is started from a cold condition and operated for 3 hours under conditions used for platform finish contour milling. Results also show that when the machine is started from a cold condition and operated for 2 hours under conditions like those used for airfoil finish contour milling, changes in alignment are in the order of only 1 mil. Similar or smaller changes are likely when operating under rough contour milling conditions since spindle speeds for rough milling are not very different from those for airfoil finish milling.

These changes will not affect airfoil contour, but they can affect airfoil thickness, platform contour, and the positions of the surfaces of the airfoil produced by the platform finishing cuttter, relative to the surfaces produced by the airfoil finishing cutter.

Changes of 1 mil are relatively small in relation to the airfoil thickness tolerance of +4 to -3 mils and the platform contour tolerances of $\pm 3$ and $\pm 4$ mils. However changes of 3 and 4 mils are relatively large. Since these are encountered under platform milling conditions, they will affect geometry produced by the platform milling cutter. Since geometry produced by the platform cutter is very important, it was concluded that blisks should not be milled with all four spindles simultaneously and that only one blisk should be milled at a time, using spindle 2, in order to maintain proper control of airfoil geometry. Changes in the Z-axis were minimized by the machine at platform finish contour milling operating speeds before actually milling, until head temperature reached operating levels, and then offsetting the X axis as subsequent changes occurred while milling.

Counterbalance System

The machine member that supports the spindles and their drive motors is moved in a vertical plane with the Z-axis positioning system. To reduce the load on this positioning system, a pneumatic counter balance mechanism is attached to the machine member through two steel cables that pass over pulleys. These cables are subjected to fretting and fatigue as they pass over the pulleys and on several occasions cables parted, making the machine inoperable until new cables were installed.

TABLE 3

CHANGES IN ALIGNMENT OF SPINDLES AND TABLES FOR NEW ENGLAND
FIVE-AXIS NC MILLING MACHINE OPERATING UNDER PLATFORM FINISH CONTOUR MILLING CONDITIONS

| Time | | Mach. Spindle and Table | Machine Positions and Position Changes | | | | | | Machine Temperature (°F) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Start Run | End Run | No. | X (in) | ΔX (mils) | Y (in) | ΔY (mils) | Z (in) | ΔZ (mil) | $T_1$ | $T_2$ | $T_3$ | $T_4$ | $T_5$ | $T_6$ |
| | 10:00 | 1 | +1.6530 | | -3.4034 | | -1.5364 | | 82 | 82 | 84 | 86 | 80 | 82 |
| | AM | 2 | +1.6552 | | -3.4055 | | -1.5365 | | | | | | | |
| (Start Cold) | | 3 | +1.6540 | | -3.4053 | | -1.5362 | | | | | | | |
| | | 4 | +1.6553 | | -3.4062 | | -1.5365 | | | | | | | |
| 10:00 | 11:00 | 1 | +1.6556 | -2.6 | -3.4015 | -1.9 | -1.5335 | -2.9 | 93 | 95 | 97 | 89 | 91 | 85 |
| AM | AM | 2 | +1.6561 | -0.9 | -3.4040 | -1.5 | -1.5333 | -3.2 | | | | | | |
| First Hour | | 3 | +1.6526 | 1.4 | -3.4035 | -1.8 | -1.5330 | -3.2 | | | | | | |
| | | 4 | +1.6518 | 3.5 | -3.4043 | -1.9 | -1.5339 | -2.6 | | | | | | |
| 11:15 | 12:20 | 1 | +1.6561 | -0.5 | -3.4006 | -0.9 | -1.5329 | -0.6 | 102 | 104 | 108 | 91 | 93 | 87 |
| AM | AM | 2 | +1.6561 | -0.0 | -3.4029 | -1.1 | -1.5326 | -0.7 | | | | | | |
| Second Hour | | 3 | +1.6524 | 0.2 | -3.4025 | -1.0 | -1.5323 | -0.7 | | | | | | |
| | | 4 | +1.6513 | 0.5 | -3.4031 | -1.2 | -1.5332 | -0.7 | | | | | | |
| 12:30 | 1:30 | 1 | +1.6562 | -0.1 | -3.4002 | -0.4 | -1.5330 | 0.1 | 104 | 108 | 112 | 92 | 94 | 87 |
| PM | AM | 2 | +1.6562 | -0.1 | -3.4024 | -0.5 | -1.5327 | 0.1 | | | | | | |
| Third Hour | | 3 | +1.6524 | 0.0 | -3.4018 | -0.6 | -1.5325 | 0.2 | | | | | | |
| | | 4 | +1.6511 | 0.2 | -3.4028 | -0.3 | -1.5331 | 0.1 | | | | | | |

NOTES:

- ΔX, ΔY, ΔZ obtained by subtraction of last X, Y, Z from immediately preceding X, Y, Z for each spindle.
- Speed - 7500 rpm, all four spindles.
- Feed Rate - 15 in/min under control of Stage 3 airfoil finish contour milling NC tapes 1 and 2, but without milling.
- Temperatures - Measurement locations given in Figure 8 (pg 20).

PERFORMANCE

The milling machine was a big factor in the successful completion of the program. It performed well enough to allow development of the complete milling process and to determine that the airfoil milling and finishing processes can be done together and were capable of meeting design requirements.

Cutting feed rates greater than about 15 in/min could not be reliably used and it was not practical to mill four parts at a time due to machine alignment changes caused by spindle bearing heating. However, in spite of these limitations, the machine made it possible to carry out the development in a way that allowed acceptable higher feed rates and machining of four parts, as soon as the first production milling machine became available.

The milling machine also served as an essential means for determining production machine requirements. Through its use in the development program, it was possible to confirm the suitability of most major design features, to establish the need for critical new and improved design features, and to develop a specification for production milling machines.

PRODUCTION MILLING MACHINE REQUIREMENTS

It was determined that production milling machines required some design features not provided in the milling machine that was designed and built for the development program. These include:

1. Spindle bearing cooling to prevent heating that will cause changes in alignment of spindles to tables at higher spindle speeds.

2. Stable operation at lineal feed rates above 15 in/min.

3. Head counterbalance system capable of continued operation over a short distance, without significant wear and without sudden failure.

Furthermore, it was determined that the following specification requirements for the production milling machine and control needed to be different from those established for the development program.

1. Improved means for changing the speed ratio of the spindle motor drive.
2. Increased rotary axis velocity capability.

A production machine specification was prepared and is included as Appendix A (pgs 301-342).

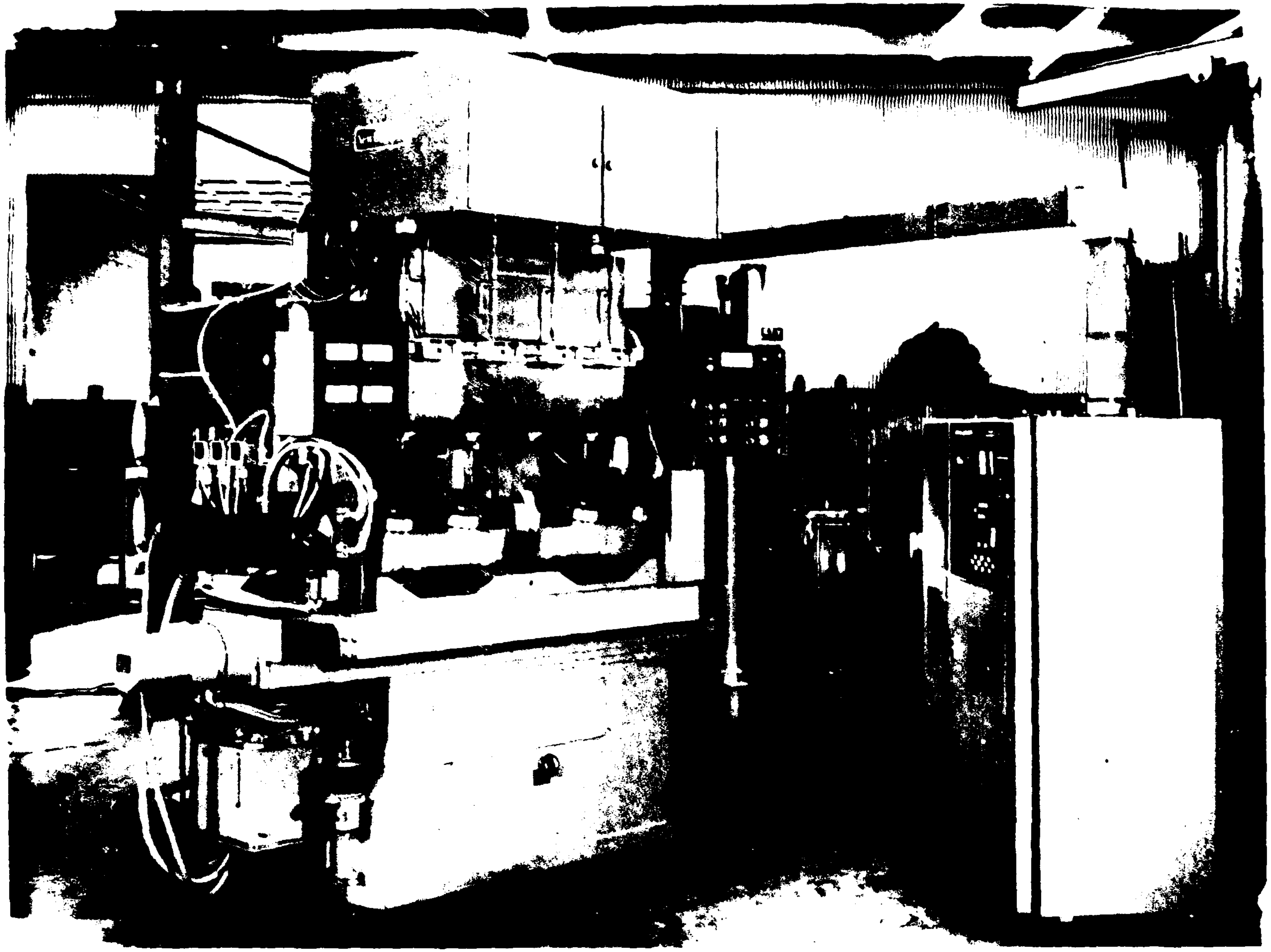


Figure 2. Developmental Milling Machine built by New England Machine and Tool Co. and General Electric Mark Century 1050 Computer Numerical Control Unit.

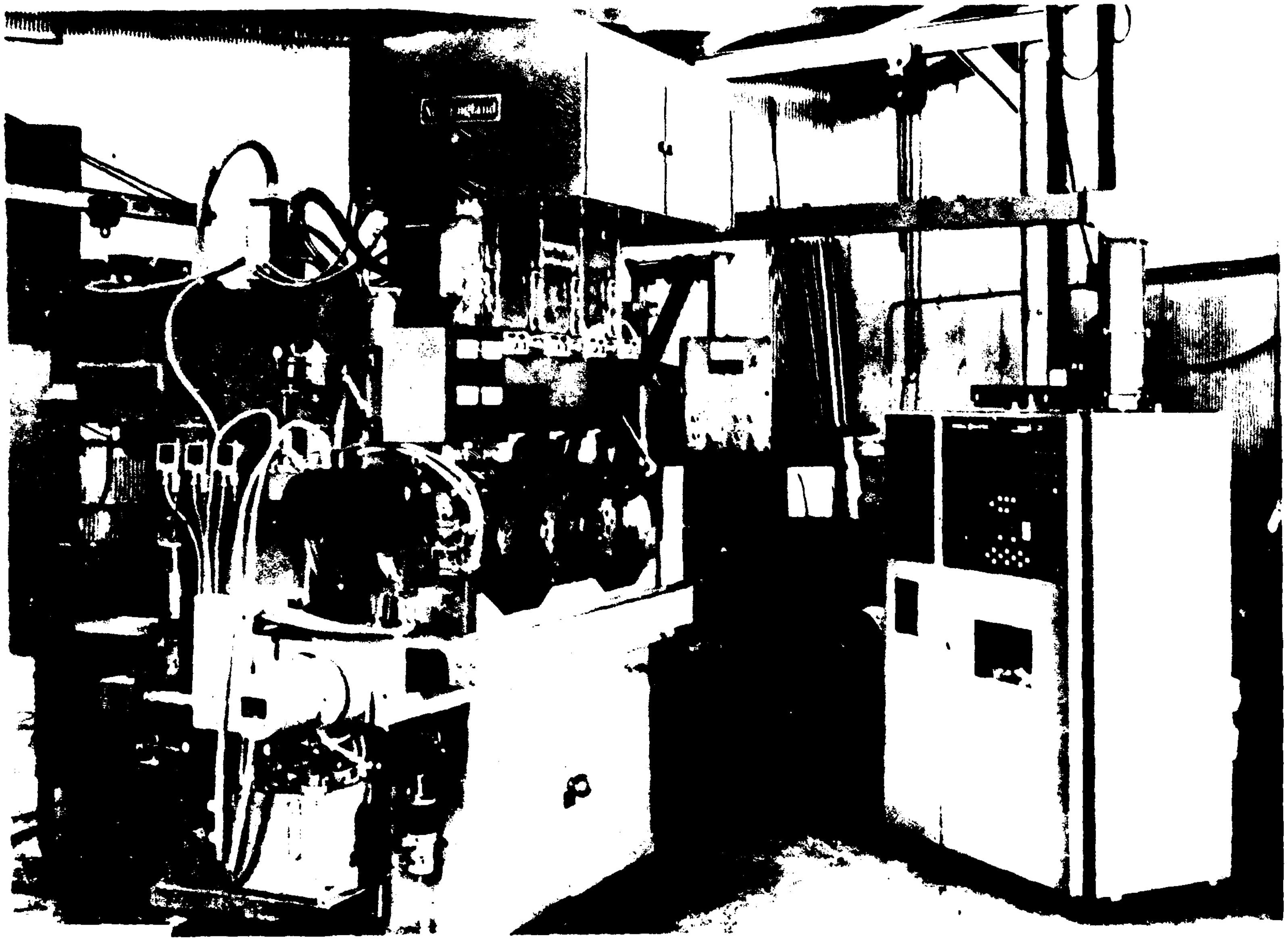


Figure 3. Developmental Milling Machine Built by New England [illegible]
Co. and General Electric Mark Century 1 [illegible]

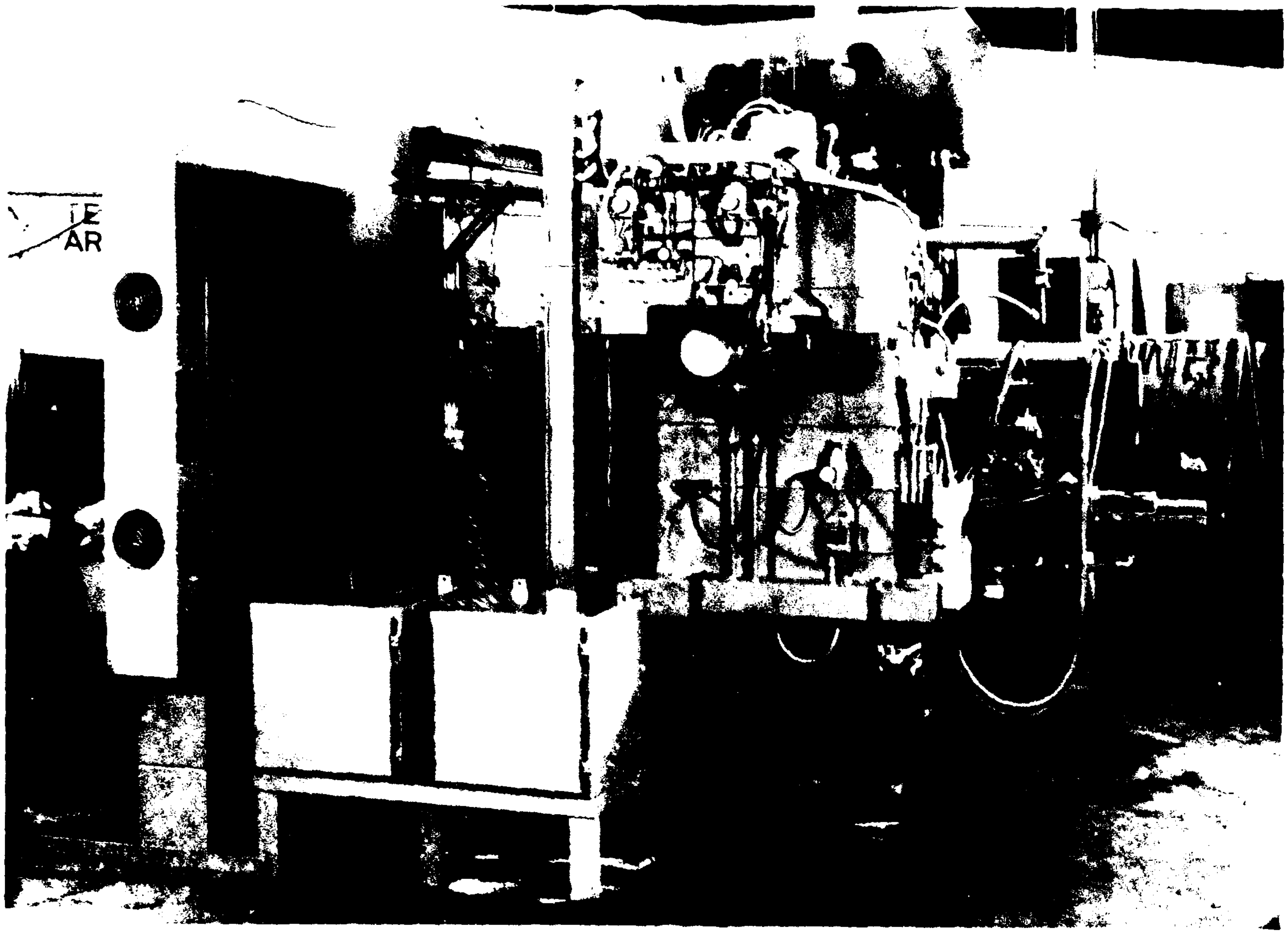
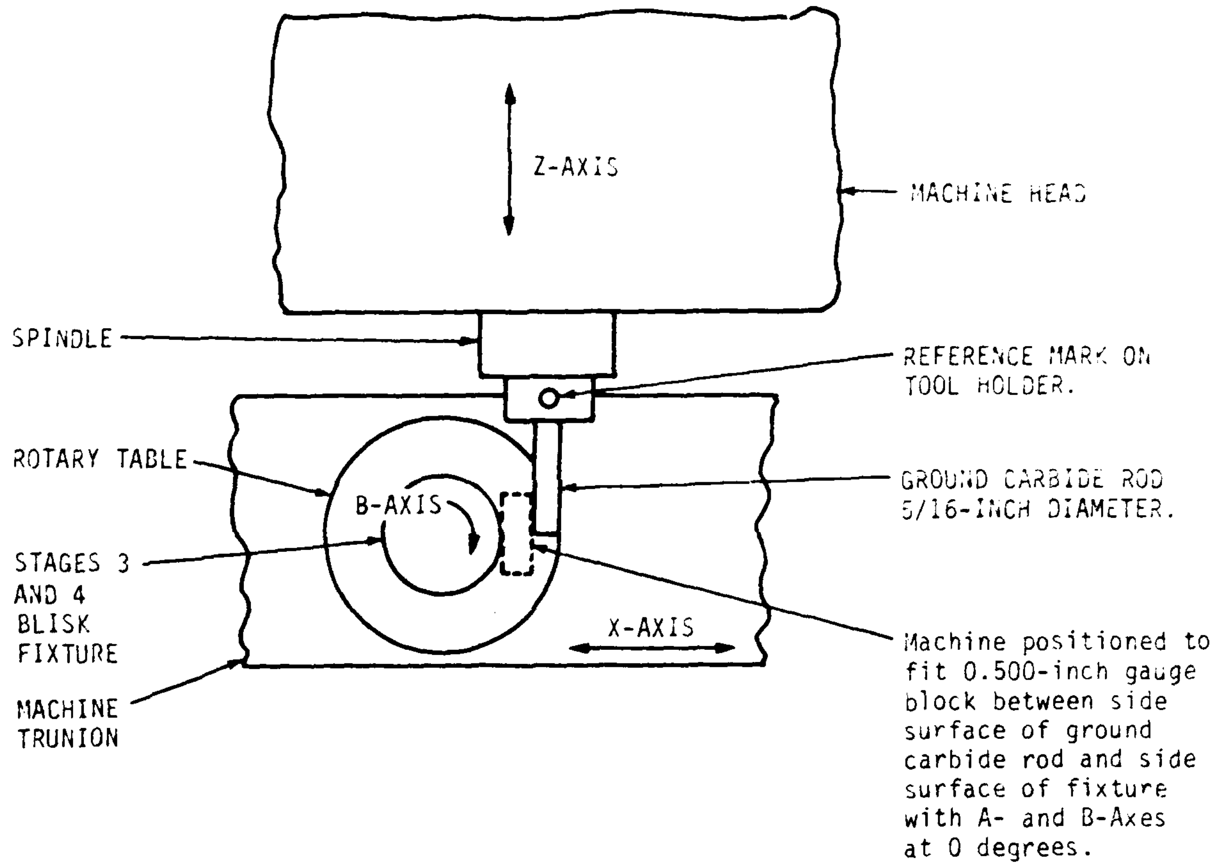
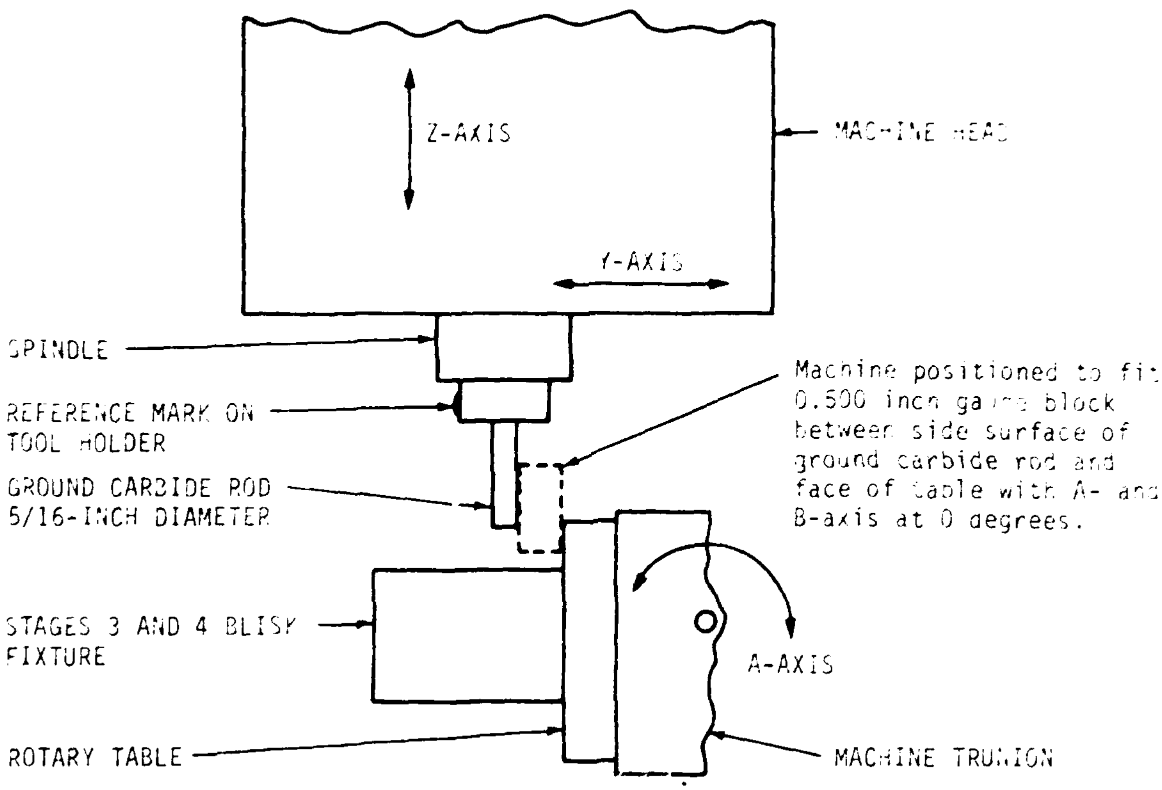


Figure 4. Developmental Milling Machine Built by New England Machine and Tool Co.



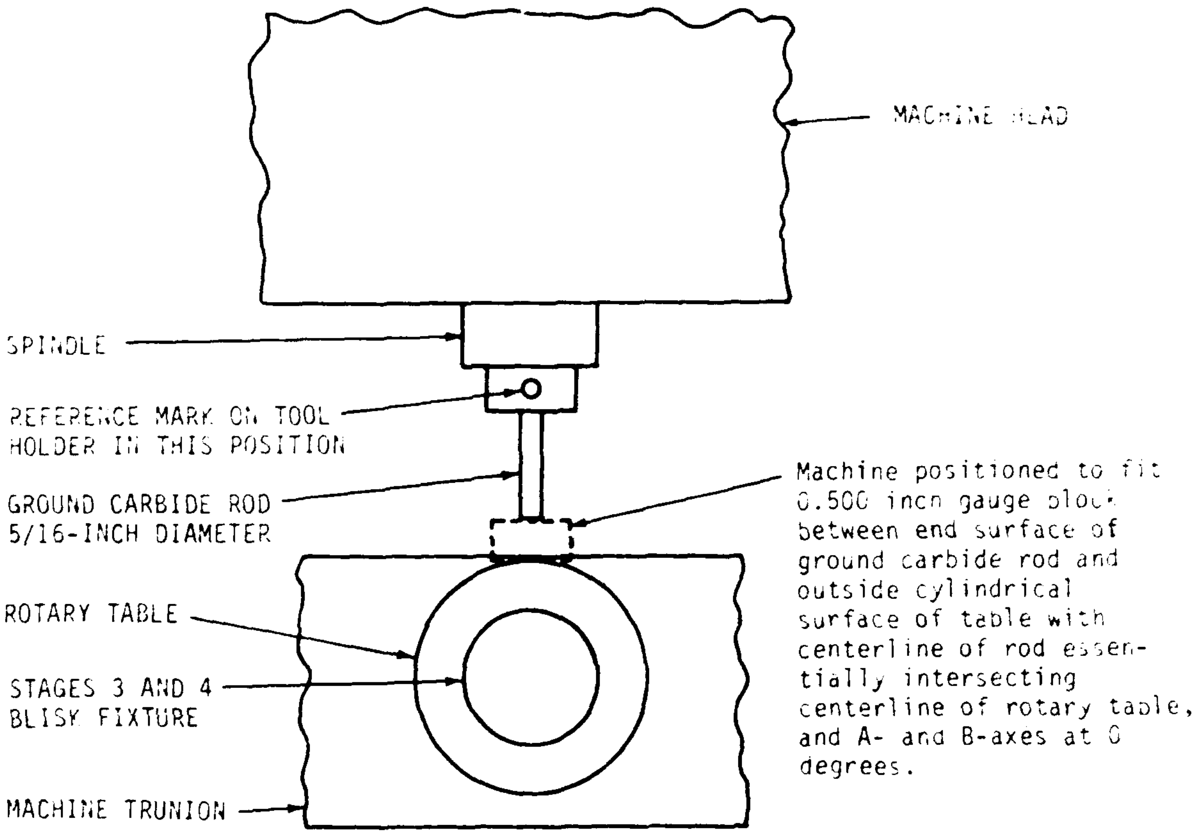

Notes: 1. Identical Y- and Z-axis positions used for all X measurements.
2. Reference mark on tool holders in same position for all measurements.

Figure 5. Surfaces Used to Determine Changes in Alignment of Spindles and Tables in X-Axis.



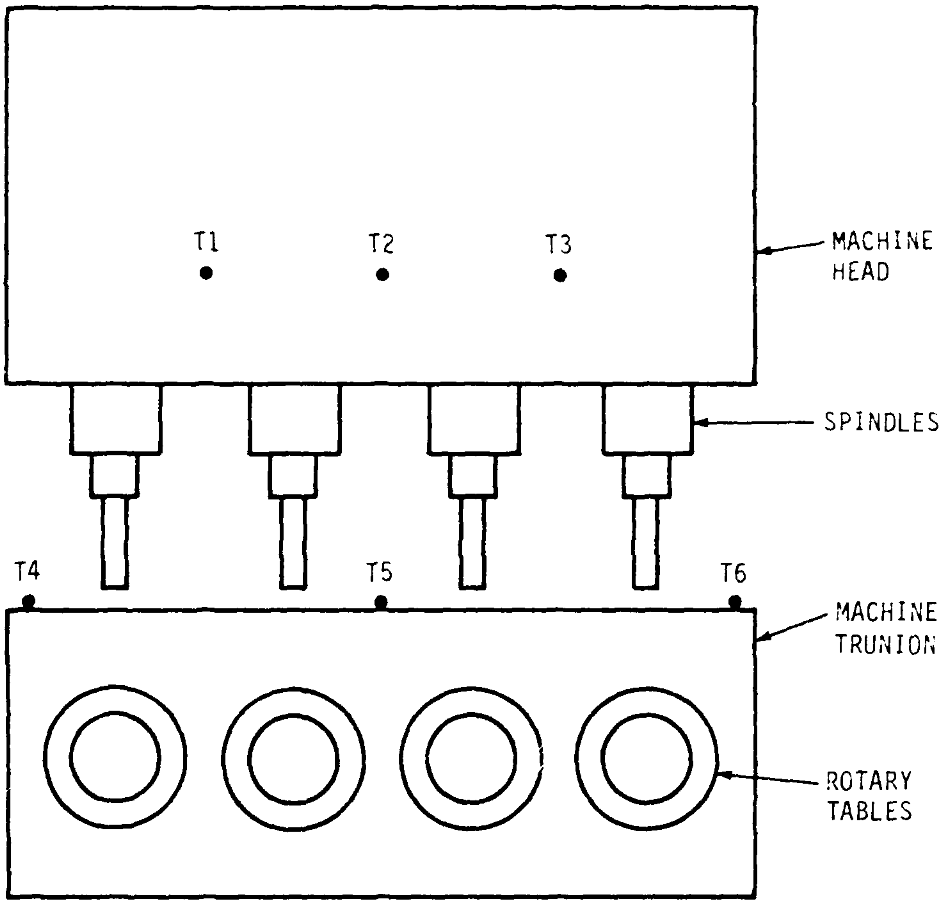

Notes: 1. Identical X and Z axis positions used for all Y measurements.
2. Reference mark on tool holders in same position for all measurements.

Figure 6. Surfaces Used to Determine Changes in Alignment of Spindles and Tables on Y-Axis.



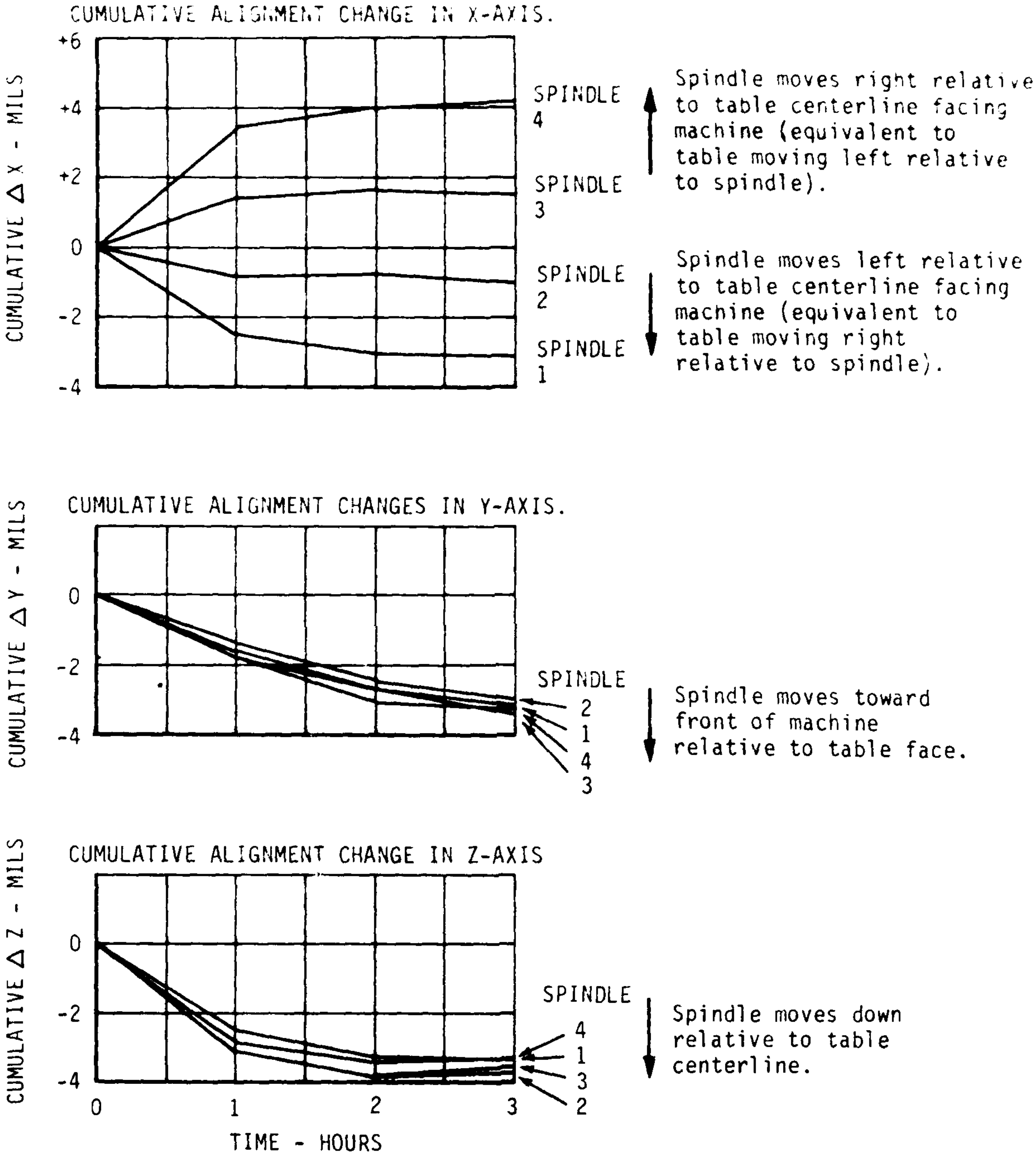

Notes:
- Identical X and Y axis positions used for all Z measurements.
- Reference mark on tool holders in same position for all measurements.

Figure 7. Surfaces Used to Determine Changes in Alignment of Spindles and Tables in Z-Axis.




Note: All temperatures measured with thermometer bulbs at locations T1 through T6.

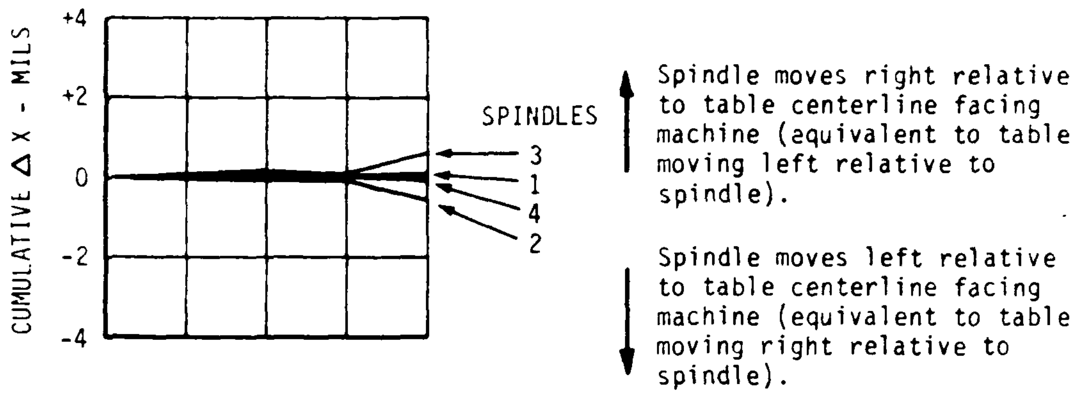
Figure 8. Locations at Which Temperatures Were Measured While Determining Changes in Alignment of Machine Spindles and Tables.



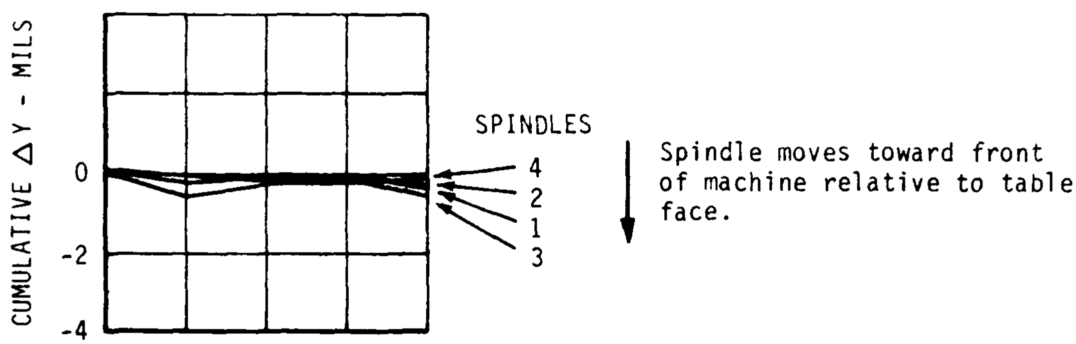

Speed - 7500 rpm all 4 spindles.
Feed Rate - 15 IN/min. under control of typical platform finish contour milling tape not milling.
Graphs plotted from data shown in Table 3.

Figure 9. Changes in Alignment of Spindles and Tables For New England Five-Axis NC Milling Machine Operating Under Platform Finish Contour Milling Conditions.

CUMULATIVE ALIGNMENT CHANGE IN X-AXIS




CUMULATIVE ALIGNMENT CHANGE IN Y-AXIS




Speed - 2300 rpm all 4 spindles.
Feed Rate - 15 IPM under control typical airfoil finish contour milling tape not milling.

Figure 10. Changes in Alignment of Spindles and Tables for New England Five-Axis Development Milling Machine Operating Under Conditions Similar to Those Used for Airfoil Finish Contour Milling.

NUMERICAL-CONTROL PROGRAMMING
FOR
BLISKS

# NUMERICAL-CONTROL PROGRAMMING FOR BLISKS

## INTRODUCTION

The first steps in the development of numerical control (NC) programs for blisk airfoil milling were the determination of the programming source and the selection of the programming language. Next, programming procedures were developed to produce NC programs from engineering data. These procedures were then used to develop programs for rough and finish contour milling Stage 1 blisk airfoils. These programs were then used to machine airfoils and were refined as needed to obtain required airfoil dimensions. Finally, programs were developed for the remaining blisk stages.

A special postprocessor was also developed specifically for the 5-axis NC milling machine and its GE1050 NC control. In addition, a program was developed to produce transparent masters for use in measuring the geometry of airfoils machined on the milling machine.

## SELECTION OF PROGRAMMING LANGUAGE AND SOURCE

The initial stages of the numerical control (NC) programming effort for blisks, revolved about the need for answers to two basic questions:

1. What is the most suitable programming source?

2. What is the best part programming language for machining an airfoil with changing cross section and which considers cutter clearance problems imposed by the adjacent blades?

With regard to the question concerning the most suitable programming source, four companies experienced in multiaxis machining were investigated. These were Sundstrand Machine Tool, Kearney and Trecker, Gurnard Manufacturing Co., and General Electric Corporate Manufacturing Services. With the exception of the last-mentioned organization, none of these firms were interested in the project.

There are at least seven NC part programming languages in use in the United States today. Of these languages, APT and GEMESH were considered the languages which are best for airfoil milling. APT (Automatically Programmed Tools), which was sponsored by the U.S. Air Force and cooperating companies of the Aerospace Industries Association of America, is the oldest and most flexible language. It allows the programmer to communicate with a computer using a special, simplified, pidgin English. The computer then generates the necessary NC tape.

GEMESH was created by the General Electric Aircraft Engine Group--Evendale, Ohio, to solve the problem of milling free-form surfaces, such as airfoils. APT was designed to handle parts whose geometry can be easily specified and cannot handle free-form surfaces. GEMESH is therefore used whenever the surface geometry is too complex to be easily handled by APT. GEMESH is designed to be used along with the APT program and the postprocessors available at General Electric.

## STAGE 1 BLISK NC PROGRAMMING

The basic objective of the blisk NC programming effort was to produce an optimum program for machining an airfoil with changing cross section.

STAGE 1 BLISK NC PROGRAMMING - Continued

## Programming Procedure

The first step in the program is to generate a mathematical, geometric, 3-dimensional model of the blade in the computer data base. The engineering drawing of the blade divides it into eleven sections, as shown in Figure 11 (pg 35). The General Electric engineers use a computer program which generates the shape of the blade at each section to meet specified design aerodynamic and performance requirements. This provides the capability of obtaining the shape, as an output from the computer, in the form of X and Y coordinates for each section. The data is available in punch card format with a printed listing. The program defines each section in two parts: a leading edge and a trailing edge part with an overlap in the middle as shown in View A of Figure 12 (pg 36). To use the engineering data for NC programming, it was necessary to group it into data for convex and concave surfaces, blended together with data for small leading and trailing edge surfaces as shown in View B of Figure 12. The data for each section was then manipulated on time-sharing to rearrange it into the required format for the APT part program.

The next step involved the generation of tabulated cylinders (TABCYL) through the coordinate points of the concave and convex surfaces for each section (see Figure 13, pg 37). The term "tabulated" refers to the fact that the surface is defined by a set of points which can be described in a table of coordinates. The resulting surface is regarded as a generalized cylinder.

A ruled surface was generated between each pair of adjacent sections. The general concept of a ruled surface can be visualized as the locus of all line positions as the line moves through space constantly in contact with two non-coincident space curves, as shown in Figure 14 (pg 38).

The next step involved the definition of cutter paths to machine the ruled surfaces using the APT program.

Because of its geometry, it is not possible to machine the Stage 1 blade by holding the milling cutter axis parallel to the surface of the blade at the local cutting zone. If this were attempted, the shank of the cutter would collide with the tip of the blade, as indicated in Figure 15, (pg 39).

To resolve this, it is necessary to tilt the cutter axis at some angle to the blade surface.

## Tool Axis Angle

Initially, the computer was allowed to determine the tool axis angle. However, all computer-aided part programming languages only examine the workpiece and tool relationship at the point where metal removal is programmed to occur. The possibility that the tool shank may collide with some other portion of the workpiece is ignored. It was, therefore, possible for the computer to provide a tape that machines the part to drawing tolerance, but which also causes the tool shank to damage the workpiece.

STAGE 1 BLISK NC PROGRAMMING - Continued

To avoid such a collision it was necessary to examine the tool axis angle at every 0.100-inch increment in the X-axis along the blade surface (see Figure 16, pg 40). First the tool axis angle for $\Delta Y$ and $\Delta Z$ between sections AA and LL of the blade was computed. This calculated angle was the tool axis angle without allowing any clearance between the tool and the air-foil surface being machined. The calculated angle was then increased to provide clearance at the cutting surface, and to avoid hitting the tip of the blade being

machined. The increase in the calculated angle was also limited, so that the tool would not hit the tip of the blade adjacent to the blade being machined. The necessary increase in the calculated tool axis angle was determined during milling tests.

## Tests of Stage 1 Blisk NC Program

Sample Stage 1 blades were machined on a 4-axis Kearney and Trecker milling machine to test the NC program. The following conclusions were drawn from this work:

1. It is possible to machine the blades of the T700 blisks on a 4-axis NC machine.

2. The analytical studies made of tool angles, to clear both the tip of blade being machined and the adjacent blades, proved to be correct.

3. A program is available for rough machining of blisk blades. This program was used later as a basis on which operations were developed on the New England milling machine designed for this project.

4. This program could also be used (in part) to check out the New England milling machine when its construction was completed.

## NC Programming of Leading and Trailing Edges

Initially, part programming of the leading and trailing edges of Stage 1 blisk blades presented a problem since the APT language was incapable of handling ruled circular surfaces over the small radii involved in these areas. Consideration was given to the use of conical surfaces, however, it was realized that this would not resolve the problem since conical surfaces have circular components. Thus, it was necessary to represent the edges as a series of planes. Ten planes were generated through the points defining the leading edge and eight planes were used for the trailing edge. Figures 17-18 (pgs 41-42) show the leading and trailing edges of the blades, as defined by planes in the program, respectively. A computer plot of the tool path, used in machining the leading and trailing eges, is shown in Figure 19 (pg 43).

## NC Programming of Roughing Cuts

Figures 20-22 (pgs 44-46) show computer plots of toolpaths programmed for rough milling of a pocket in a Stage 1 blisk.

STAGE 1 BLISK NC PROGRAMMING - Continued

Simple blisk blades were successfully rough machined, following which a decision was made to extend the tip of the blade by 0.10 inch, to allow for metal removal in that area during the finishing process. For similar reasons, the tool paths in the APT program were altered to allow a minimum of 0.015 inch of stock to be left on the rough machined blade instead of the initial stock thickness of 0.005 in. Consequently, it was necessary to adjust the clearance angles between the cutter and the blades.

When rough machining the pocket between adjacent blades, it was necessary to machine away a spur which remained midway between the blades. The spur was caused by a divergence between the entrance and exit toolpaths as they generated the leading and trailing edges. The original tape which roughed the pocket started to machine along the blade surface, then moved over to machine the spur, and then moved back again to machine the blade surface.

This caused a discontinuity in the stock which had to be removed by the finish cuts. The rough machining tape was modified so that the tool completes machining one side of the blade before it removes the spur of metal. This results in a more uniform amount of stock being left on the blade surface at any given section.

The tool clearance angle for the roughing operation was altered. By decreasing the angle by 2 degrees, the cutter was able to remove more stock, therby reducing the size of the steps left on the roughed surface.

When the geometric definitions of the blisk are entered in he APT program, the APT surface definitions are converted to a binary data file. This eliminates the need for APT to process the geometric surfaces each time the program is run, thereby reducing computer time and cost.

Operator Messages on Tape

The General Electric 1050 control system has the ability to read and transmit messages to the operator, as well as the ability to read operational instructions from the punched tape. Any messages contained in the tape are displayed on the 8-line, 256-character alpha-numeric readout on the control panel.

Because the blisk NC tapes are long and are contained in several reels, it is important that the machine operator be given every aid to assure that the correct tape is loaded in the reader. It is also important that he is aware of what the next section of the tape is about to perform. Operator messages, identifying each tape, were added to the beginning of each tape. Operator messages were also added throughout the tapes, to inform the operator as to which radial height cross-section is about to be machined.

STAGE 1 BLISK NC PROGRAMMING - Continued

Stage 1 Blisk NC Finish Machining Programming Problems and Solutions

During early tape tryouts, it was observed that the feed rate, relative to the part surface, was somewhat lower than expected. This situation arises whenever a rotary and a linear axis move together in the same direction. When this occurs, the postprocessor calculates the feed rate based on one of the axes. The result is that, although the machine axes are moving at the desired speed, the relative speed of the tool across the part surface is reduced. This problem was resolved by arranging the postprocessor to calculate the feed rate based on the relative motion of the tool and part. The postprocessor also checks that none of the maximum feed rates, of the different axes are exceeded.

During tests of the first finish machining tape for the Stage 1 blisk blade, on the 5-axis New England milling machine, a flat spot was found on the convex side of the trailing edge of the blade. This was caused by a large linear movement that had been inadvertantly programmed for that area in the finishing tapes. In correcting the problem, some undercuts were observed on the concave side in the same area. Subsequent modifications to the part program eliminated both problems.

Further machining tests indicated that a mismatch occurred on the blade surface at the point where the cutting tool is changed from a 5/16-inch to a 1/8-inch diameter to machine the platform. Under the original procedure, an undercut could occur at the base of the blade as a result of the mismatch. To resolve this problem, the part program was changed so that any mismatch would result in stock being left on the blade.

The milling trials indicated a need for an extension of the chord of the blade. Changes were made in the part program to permit extension of the chord by any amount for any section. Finishing tapes were produced with the chord extended a total length of 0.015 inch. The tapes were subsequently tested and found to be satisfactory.

During the course of additional tests with the Stage 1 blisk, it was noted that, at times, the envelope remaining after rough contour milling was too small to allow the finish contour cutter to make a full clean-up cut. Investigation showed that whenever the rough cutter entered a full 180 degree arc of cut, it was deflected into the blade surface. This caused insufficient stock to be left at the center sections of the blade. The rough milling program was modified to leave an additional 0.010 inch per side during roughing cuts, to a 0.025 inch total per side.

A similar effect was noted when the finish cutter was milling the fillet between the blade and platform. This resulted in an undercut of the fillet, starting at the stacking axis of the convex side of the blade and continuing to the trailing edge. New tapes were generated to leave an additional 0.003 inch of stock on he last four passes near the platform. The four passes are then repeated to machine the fillet to the required envelope.

Tape and machine tryouts followed by abrasive flow machining of edges showd that the final chord length varies as a function of blade thickness and that the blade thickness tends to be larger than called for by the tape. To compensate for this, the tape was reprogrammed to reduce the blade thickness by 0.005 inch.

STAGE 1 BLISK NC PROGRAMMING - Continued

### Inspection Glass Layouts

An inspection glass layout of Sections B-B, D-D, F-F, and H-H of the Stage 1 blisk blade (Figure 11, pg 35) was prepared for use by Quality Control, with the aid of an APT program developed for this purpose. It generated a 10X layout of each airfoil section increased by 0.0625 inch all around, to allow for the radius of the sylus of the airfoil tracing machine. Figure 23 (pg 47) shows Sections BB and DD. The tracing machine is described in the Inspection Process Development section (pgs 217-220) of this report.

## PART PROGRAMMING OF STAGE 1 BLISK PLATFORM

The first step in part programming the platform is to define its geometry. The cross-sectional view of the platform, as shown in Figure 24 (pg 48), shows that the platform is not a straight line, i.e., it is not a cylinder or a cone. Instead, it is defined as a series of Radii AA for nine axial Locations AC along the platform.

The APT language is capagle of defining many types of surfaces; however, it cannot define a surface of revolution. A surface of revolution is defined by fitting a planar curve through the AA and AC coordinates and then revolving the curve through 360 degrees, thereby creating a surface. Since this convenient surface definition was not available, it was necessay to represent the platform surface as 10 separate surfaces. Each surface was defined as a cone containing every two adjacent coordinate points.

A subprogram was written so that, as the cutting tool moved in the direction of AC, a check is made to determine the appropriate cone to represent the platform in that local area. The cutter enters the workpiece at the trailing edge of the concave surface of the blade. Since the platform is wider at the trailing edges of the blades than at the leading edges, the cutter is programmed to initially remove the stock by following the concave surface to a point which is equidistant to both blades. It then machines its way back out of the workpiece by following the convex surface of the adjacent blade. When sufficient stock in the center has been removed, the cutter finishes the platform by following the entire concave and convex surfaces. Figures 25-27 (pgs 49-51) show computer plots of tool paths involved in finish machining of blisk platforms. The tool paths are shown spaced 0.04 inch apart, instead of the actual 0.01 inch to simplify the plots. Tool paths along the surface of sample airfoils are visible in Figure 28 (pg 52).

### Stage 1 Blisk Platform NC Programming Problems and Solutions

A 1/8-inch diameter ball cutter, with a 5/16-inch-diameter shank was used in platform finish milling. To avoid interference between the tapered shank of the cutter and the blade adjacent to the platform fillet, or the shank and the adjacent blade, it was found that the taper half-angle should not exceed 15 degrees.

STAGES 2 THROUGH 5 BLISKS NC PROGRAMMING

The NC programming procedures, observed for airfoils and platforms of Stage 2, 3 and 4, and 5 blisks were similar to those previously described for the Stage 1 Blisk NC programming (pgs 23-28). A "family of parts" approach was followed in programming the other blisks, to realize programming efficiency and to capitalize on improvements made in the Stage 1 blisk program as a result of 5-axis milling machine tryouts. At the outset of each new program, the engineering computer coordinate data, which defines the airfoil shape at each section of a blisk blade, was reformatted to suit the APT program. Tabulated cylinders were then generated and ruled surfaces were created between adjacent tabulated cylinders. The geometry package for each stage was completed with the definition of the blade platform.

As was the case with the Stage 1 blisk, calculations were required to determine the cutting tool axis clearance angle, to avoid collision of the tool shank with the work piece (see Tool Axis Angle, pg 24). Since these hand calculations were very laborious, a computer program was written and used for all other stages. The program also computes the minimum tool length required to machine a given blisk. The application of this information ensures maximum tool stiffness for each stage.

NC Programming of Stage 2 Blisk

During the course of Stage 2 blisk NC programming, the cutter length was shortened by 0.5 inch to increase rigidity. This tends to reduce the thickness variability of the blisk blades. In addition, to prevent the spindle head from colliding with the A-axis gear housing, it was necessary to move the blisk blank out 1.5 inch in the Y-axis.

Following the above changes, it was found that the roughing and finishing tapes caused the tool shank to rub against the blades when the platform was being machined. To correct this problem, it was necessary to reprogram the tapes and to make the necessary adjustments to airfoil thickness and chord length.

Later, it was necessary to modify the finishing tapes to change the leading and trailing edge chord extensions from 0.007 inch to 0.004 inch and to reduce edge thicknesses. This made the Stage 2 tapes compatible with the Stage 1 tapes used in producing the first piece of engine hardware.

Toward the end of the Stage 2 blisk NC programming effort, a study was performed to resolve the tool deflection problem, occurring in the rough milling procedure, when the cutter deflected into the blade surface immediately after it began to cut 180 degrees around its forward motion. This created slight marks on the finished airfoils when the cutter was beginning to dull. These marks appeard at radial heights 0.125 inch apart. Only the Stage 1 and 2 blisks were affected. To correct the problem, the roughing programs were changed so that 0.005 inch additional stock was left in the problem areas. The new tapes for both stages were successfully run on the production milling machine and were subsequently incoporated in the distributed numerical control (DNC) system.

STAGES 2 THROUGH 5 BLISKS NC PROGRAMMING - Continued

NC Programming of Stages 3 and 4 Blisk

An undercut was discovered in the platform tape of the Stage 3 blisk. This problem was found to lie in the ro[illegible] used in machining of the blade edges. The blisk platforms are represented in the part program by a series of cones. In Stages 1, 2 and 4, the leading edge profile is contained in a single cone; however, in Stages 3 and 5, the leading edges are contained in two cones. Since, in the case of the Stage 3 blisk platform, the edge machining routine did not accommodate the second cone, an undercut occurred. The routine was changed for this blisk to provide for the second cone on the leading edge profile of the platform.

Inspection of Stage 3 and 4 test pieces indicated that the blade thicknesses should be reduced in the program. Accordingly, a new set of finishing tapes was generated with the thickness programmed 0.005 inch below nominal. In addition, the chord length was reduced by limiting the leading and trailing edge extensions to 0.004 inch instead of 0.010 inch and 0.007 inch, respectively.

The new edge extension capability, described for the Stage 5 blisk below, was utilized to extend the chord in increasing amounts toward the blade tip, where the largest amount of material is removed by the abrasive flow machining process. However, airfoils generated by these tapes proved to be thinner than expected. In addition, shallow cutting lines appeared at various levels along the convex surface of the Stage 3 airfoils, running from leading to trailing edge.

To resolve these problems, the ball tangency routine was reviewed to check the calculation that determines when the cutting tool should transfer control from one ruled surface to the next. Since this routine uses an approximation of tool location, and the Stage 3 convex airfoil has a much larger concave attitude, when viewed from tip toward platform, than other stages, it was concluded that a closer approximation of tool location was required to make the decision for transfer of ruled surfaces. A new set of tapes was generated for Stages 3 and 4, including a change to 0.003 inch thickness below nominal instead of the previous 0.005 inch. This resulted in an improvement in the cutting lines, although they did not disappear entirely. The problem was ultimately solved by increasing the tool angle, with respect to the airfoil surface, by 2 degrees.

Measurements made on the Stage 3 blisks, produced on the production 5-axis milling machine, indicated that a new set of airfoil finishing tapes was required to reduce the thickness by 0.002 inch from that incorporated in the development tapes. These were generated and formatted for the DNC system. The tapes were later tested successfully on the production milling machine.

NC Programming of Stage 5 Blisk

Two problems were encountered during process tryouts on the Stage 5 blisk blade. The first problem centered on the irregular and undercut leading and trailing edges produced by abrasive flow machining. This was resolved by increasing the extensions on the leading edge from plus 0.004 inch to plus 0.012 inch, and the trailing edge from plus 0.004 inch to plus 0.006 inch.

STAGES 2 THROUGH 5 BLISKS NC PROGRAMMING- Continued

NC Programming of Stage 5 Blisk - Continued

The second problem involved cutter shank rubbing at the blade tip during rough machining operations. It was found that the program did not make sufficient allowance for the fact that the Stage 5 blisk platform slopes in the opposite direction to that of the Stage 1 blisk. To resolve the problem, the program was modified to provide better clearance angles.

Later, it was found necessary to generate a new set of finishing tapes with the blade thickness programmed for 0.002 inch below nominal. In addition, improvements were made in the platform fillet area to eliminate local undercutting where the platform surfaces change contour during the generation of the leading edges. The platform program changes led, in turn, to changes in the blade edge machining routine. A disadvantage in this routine had been the fact that chord extensions had to be the same for the entire length of the blade. Since the abrasive flow machining process does not remove a constant amount of material from the entire length of a given edge on each stage blisk, the edge routines were changed so that the program could compensate for the AFM process characteristics on any stage.

A new routine was written to permit extension of each airfoil cross section a different amount, as may be required by circumstances. This was accomplished by moving the data base for the edge point clusters along the airfoil meanline to the desired extension. To accomplish this, it was necessary to write a program which calculates the direction vectors in which to move the edge point data base.

Another problem concerned the conical section of the blisk just below the platform and forward of the leading edge of the blades. Ordinarily, this surface is finish-machined prior to platform machining. It was noted that slight tool marks were cut into this surface. This problem was eliminated by increasing the tool clearance above this surface.

An investigation was conducted to determine if sufficient clearance was available to permit the use of new 0.250-inch-diameter cutters instead of the original 0.1875-inch-diameter cutters. It was expected that an improved surface finish would result due to the greater rigidity and radius of the new cutters. The results of the investigation were positive; accordingly, both the roughing and finishing tapes were changed to accommodate the larger diameter cutters.

Problems and Solutions

Further testing of the blisk program on the 5-axis milling machine showed a need for an increase in the relative velocity of the cutting tool over the blade surface. The tapes limited the linear axes to 30 in/min, the B-axis to 2.0 rpm, and the A-axis to 2.0 rpm at cutting feeds. Since the B-axis and the X-axis work contrary to each other on some moves, it is necessary to move the X-axis faster than 30 in/min to maintain a relative velocity of 30 in/min of the cutting tool over the blade surface. The B-axis also reduces that velocity to less than 30 in/min on some moves. However, the first production five-axis mill allows 60 in/min feed rates for each linear axis, 4 rpm for the B-axis, and 4 rpm for the A-axis.

STAGES 2 THROUGH 5 BLISKS NC PROGRAMMING - Continued

Problems and Solutions - Continued

Therefore, the program was changed and a new set of production Stage 1 tapes was generated to mill blades at a relative velocity of 40 in/min between the tool and blade surface.

Another change was made to identify each blade finish milling pass consecutively, from the first to the last, with an item number (Item No.). Each of the seven blade-finishing tapes used for development milling began with pass Number 1, and sent a message to the GE 1050 NC control to be displayed so that the operator would know his progress through that tape. However, when the DNC system was to become operational, those tapes were to be treated as one long tape, which would mill from the tip of the blade to the platform without interruption. In order to re-start the tape (or data file) in the event of a failure part of the way down the blade, it is necessary to have each of the 169 passes identified with its own Item Number. This enables the distributed numerical control (DNC) software to search for a logical pick-up point in the data storage of the combined tapes.

The four platform fillet tapes, for the Stage 1 blisk, also have this feature and use Items Nos. 1 through 89 to identify the passes contained in those tapes which are executed as a single tape in the DNC system.

Later, when the tapes were tried on the new production milling machine, a few slight dwell marks appeared in the fillet area, due to short moves where the platform surface changes. When these small moves occur, the feed rate slows from 40 in/min to as low as 2 in/min leaving dwell marks on the fillet surface. A new tape was generated to correct this condition.

POSTPROCESSING

Postprocessing is the final computer operation in the APT system. It performs all computer operations necessary to combine cutter path data with additional information required by the machine tool and presents them in a format which is understood by the NC machine control. For each type of control system, the postprocessor translates the universal APT language into the control's "machine" language. Every new machine tool and control combination requires that postprocessor software be written for it. This software is then stored in the Honeywell 6000 computer memory and is called into operation whenever an APT program for the blisks is being processed.

The task of developing the postprocessor was assigned to the General Electric Aircraft Engine Group in Evendale, Ohio. This organization provides all postprocessors used on NC machine controls in the General Electric Lynn, Mass., and Evendale, Ohio plants. It also makes automatic updates of postprocessors to accommodate all changes in the APT system.

POSTPROCESSING - Continued

## Machine Tryouts of Postprocessor

Several machine tryouts were conducted during tests of the postprocessor. In the first tryout, the test program was "dry run", i.e., with fixture and workpiece in the machine, but without the cutting tool in the holder.

Next, all five axes were exercised in machining a fillet in the edge of a disk. This test successfully demonstrated that the part program, the GE 1050 NC control and its postprocessor were, very likely, performing satisfactorily.

The tryout did indicate areas where some modifications were necessary. The most significant of these were observed in two incidents. In the first, it was noted that if the part geometry requires that the A-axis rotate beyond -5 and 95 degrees, it is necessary for the B-axis to rotate 180 degrees to bring the required motion within the A-axis travel. This requires that the X-, Y-, and Z-axes move so that the tool is in its proper location after the B-axis has turned 180 degrees. However, the X-, Y-, and Z-axes take the shortest route, which is right across the part and fixture.

In the second incident, it was observed that, if the part program calls for a large rotary movement in the Aor B-axis, a point on the surface of the part is swung through a large arc. However, if the tool is trying to keep in contact with this point, the X-, Y-, and Z-axes resolve a vector to reach the final destination of the point and the locus of this vector is a chord across the arc, therby producing a scalloped surface.

It was realized that these were not postprocessor problems as such but, in order to avoid them, it was necessary to break the rotary motion into a number of smaller incremental moves. This could have been done manually by the part programmer, but it was considered preferable to have the postprocessor monitor the incremental movements of the Aand B-axis and automatically break them into smaller increments if a potential problem existed. A feature was subsequently added to the postprocessor which accomplished this.

In a third tryout, it was planned to check the rough and finish tapes for the Stage 1 blisk on the 5-axis New England machine, and determine if other postprocessor or control problems could be identified.

## Machining Time

The actual machining of a pocket was found to take longer than calculated. This was investigated and found to be caused by the control preventing the machine from operating at the part program feed rates. This was caused by the setup configuration of the control. Four MSD (machine setup data) tapes were generated for use in an investigation of this problem. In addition, test tapes were created to determine the maximum speed at which the machine can operate and still meet specification requirements.

POSTPROCESSING - Continued

Machining Time - Continued

As part of this investigation, a version of the postprocessor program was modified to print out the accumulated toolpath distance and was used in evaluating the machining cycle time as a function of the tool feed rate. This helped to identify areas where increased feed rate could be incorporated. It also showed that the postprocessor allowed the B-axis rotation speed to exceed limits when the tool was in rapid traverse mode. Both the part program and the postprocessor program were subsequently modified to eliminate these problems.

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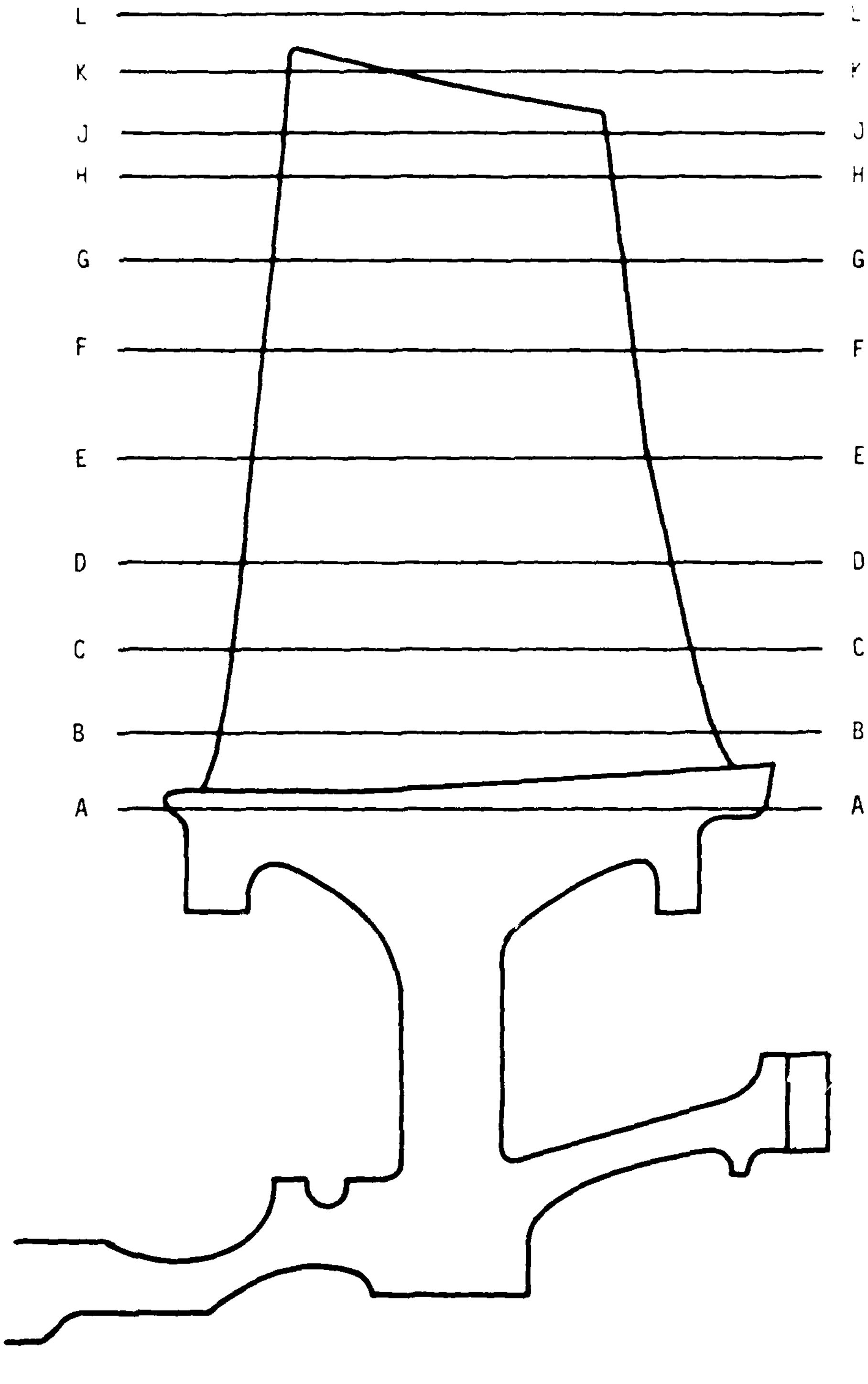
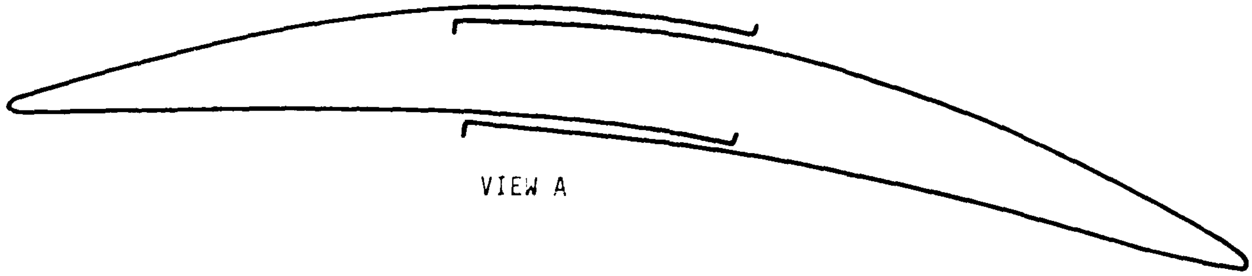


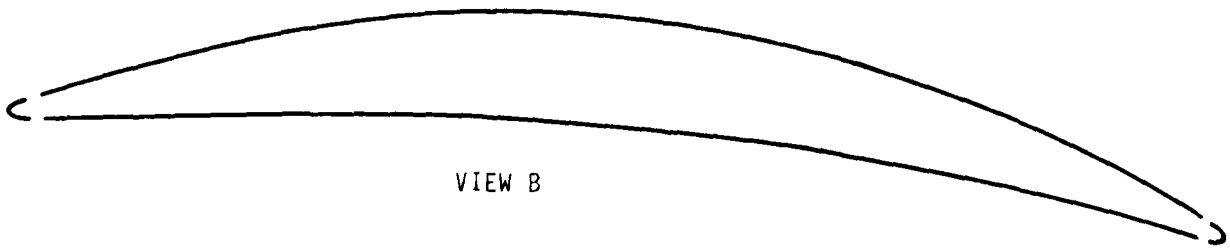

Figure 11. Stage 1 Blade With Sections as Defined on Engineering Drawing.

OUTPUT FROM AERO-DESIGN COMPUTER PROGRAM



VIEW A

REQUIRED INPUT TO APT PART PROGRAM



VIEW B

Figure 12. Airfoil Sections Defined by Computer.


Figure 13. Computer Plot of TABCYLS For Sections B and K.

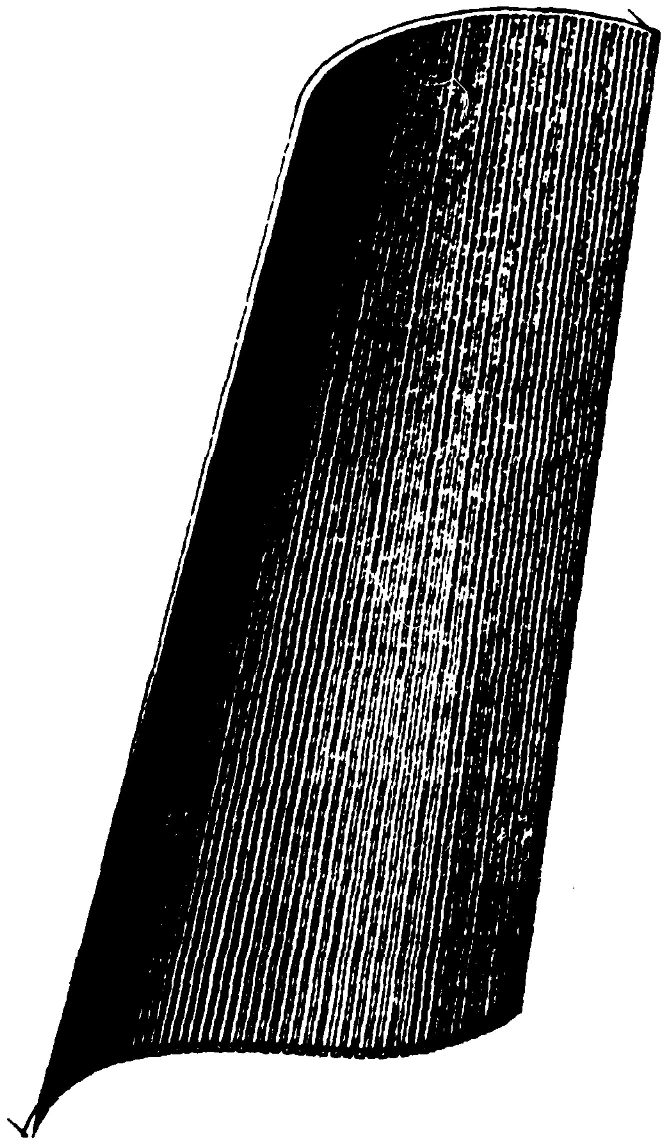


Figure 14. Example of a Ruled Surface.

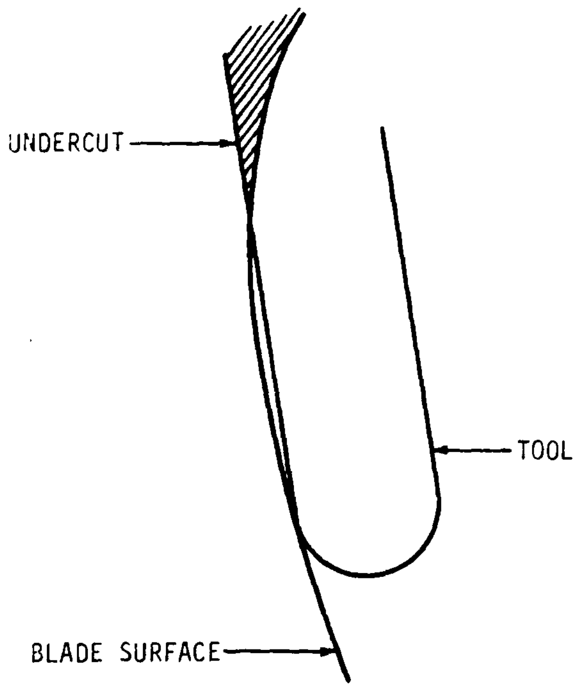



Figure 15. Tool Parallel to Blade Surface at Contact Point Causes Undercut of a Concave Surface.

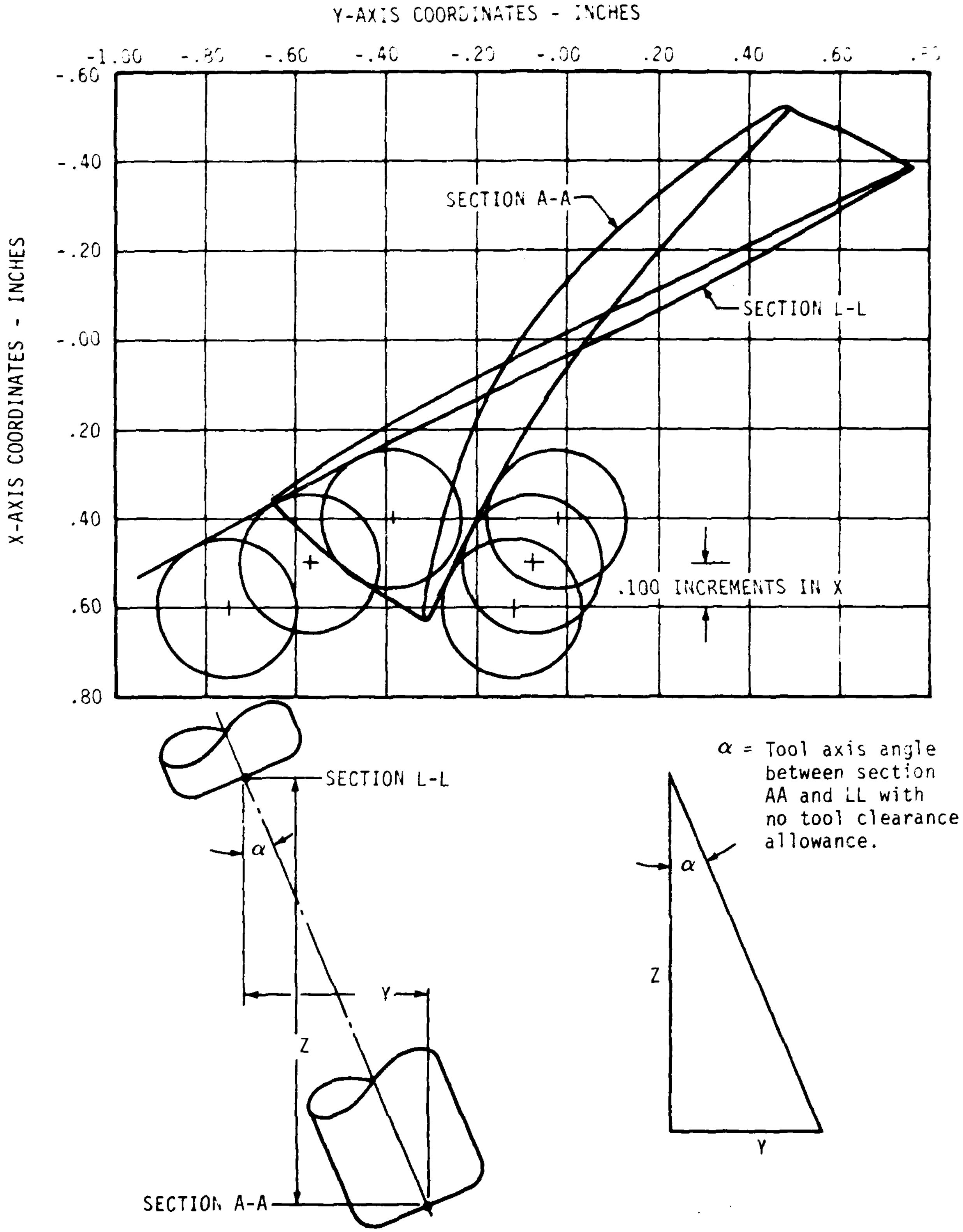



Figure 16. Tool Axis Angle.

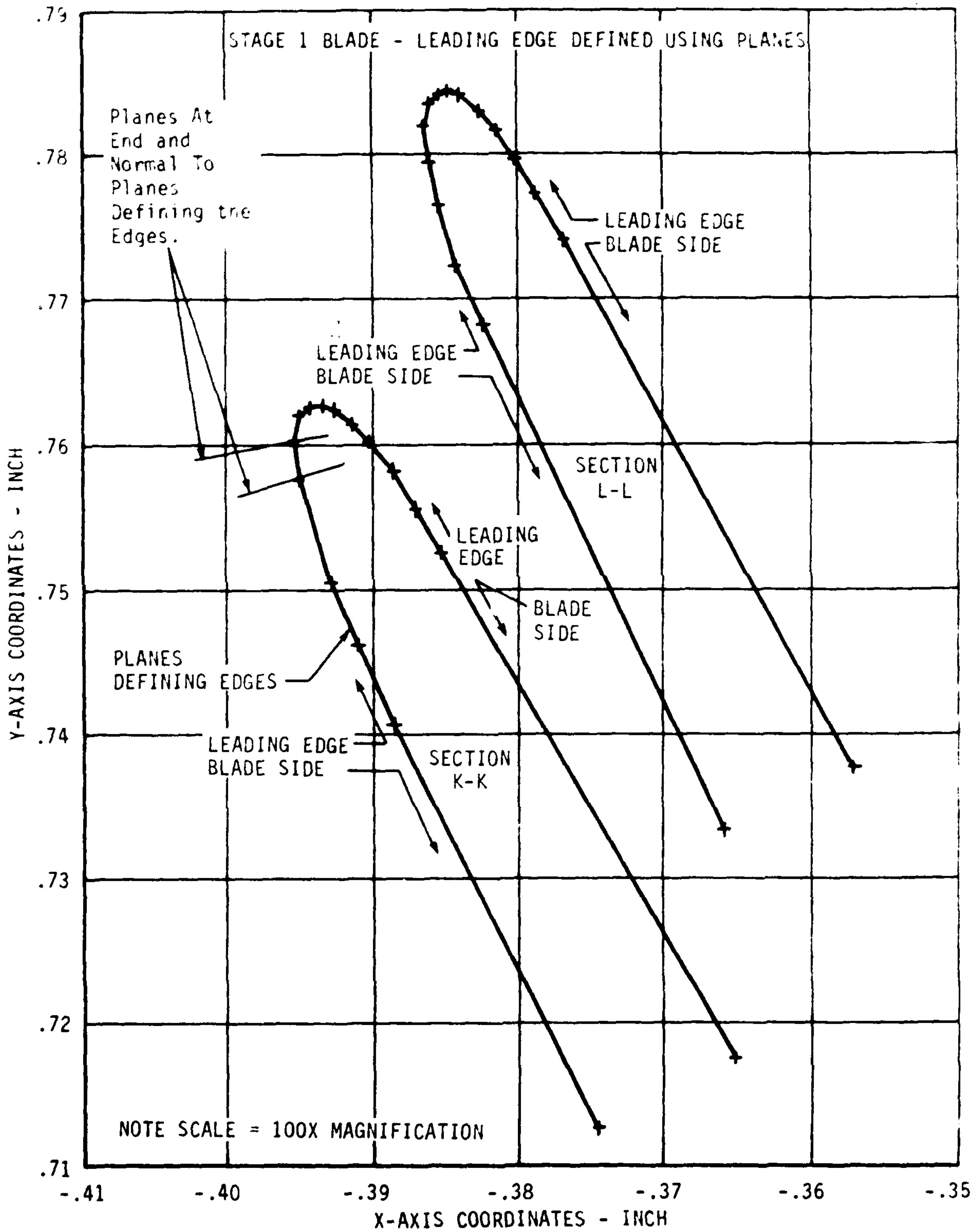



Figure 17. Leading Edge of Stage 1 Blisk Blade as Defined in Program.

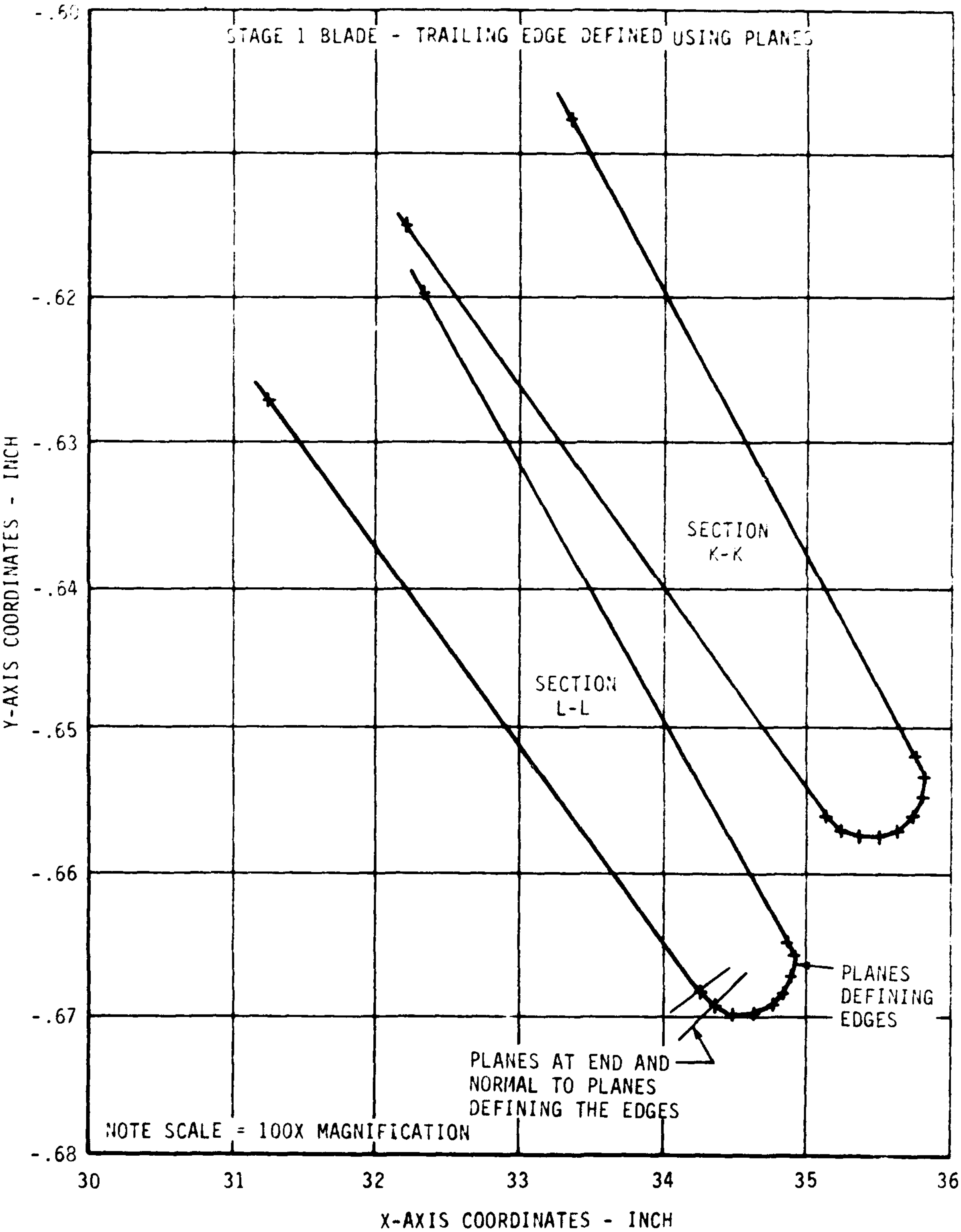



Figure 18. Trailing Edge of Stage 1 Blisk Blade as Defined in Program.

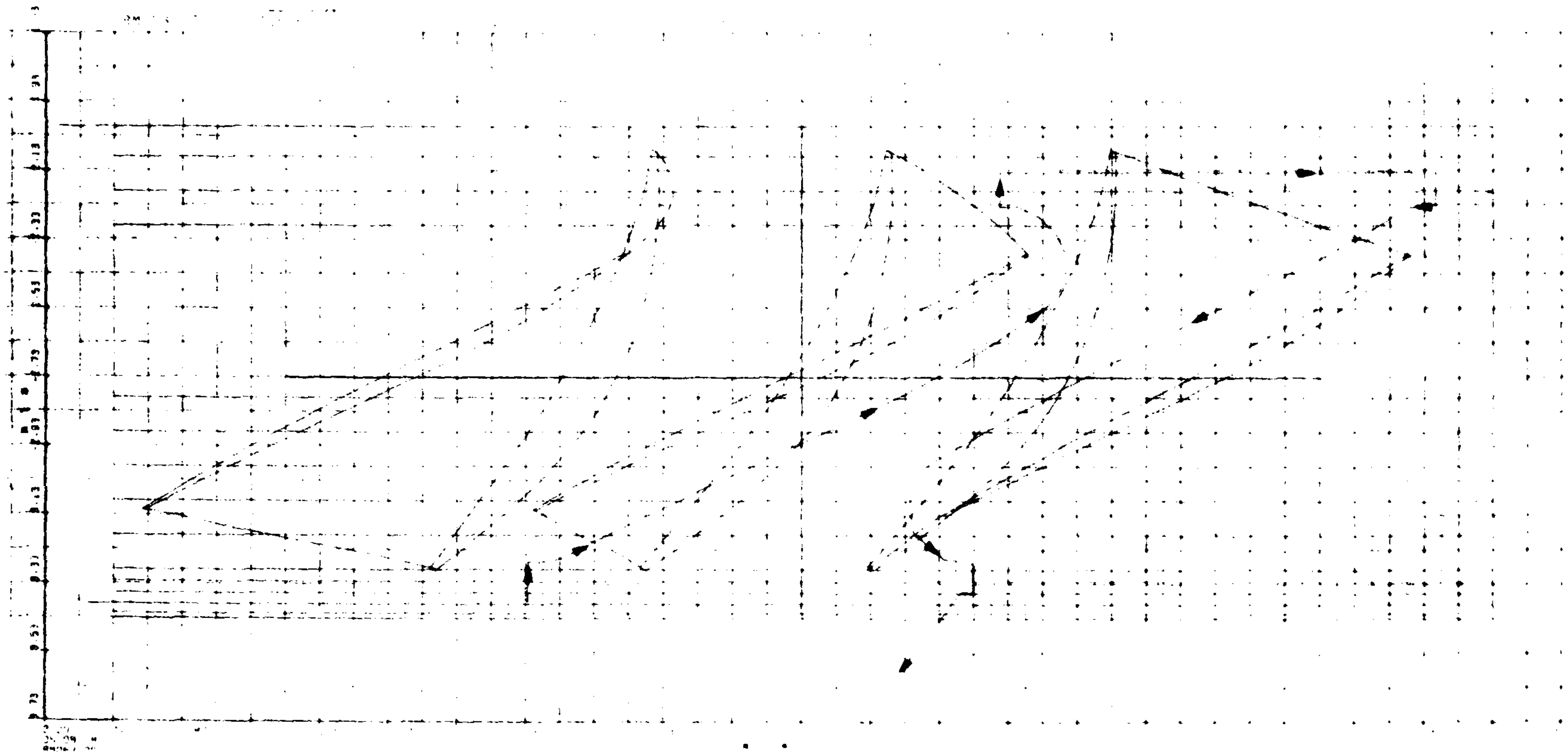


Figure 19. Computer Plot of Tool Path to Machine the Tip of the Blade Including the Leading and Trialing Edges for Stage 1 Blisk.

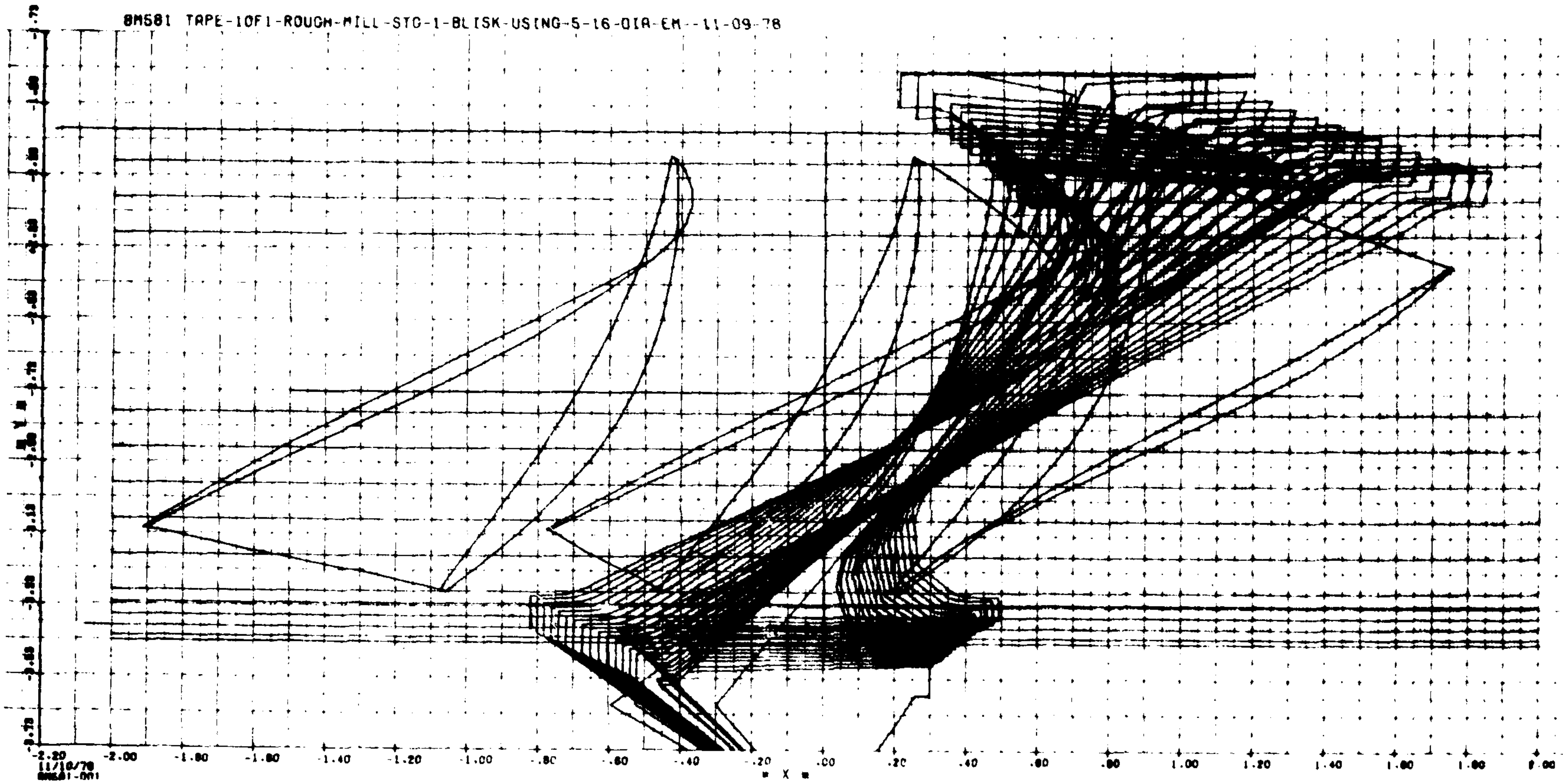



Figure 20. Computer Plot of Tool Paths to Rough Mill a Pocket for Stage 1 Blisk.

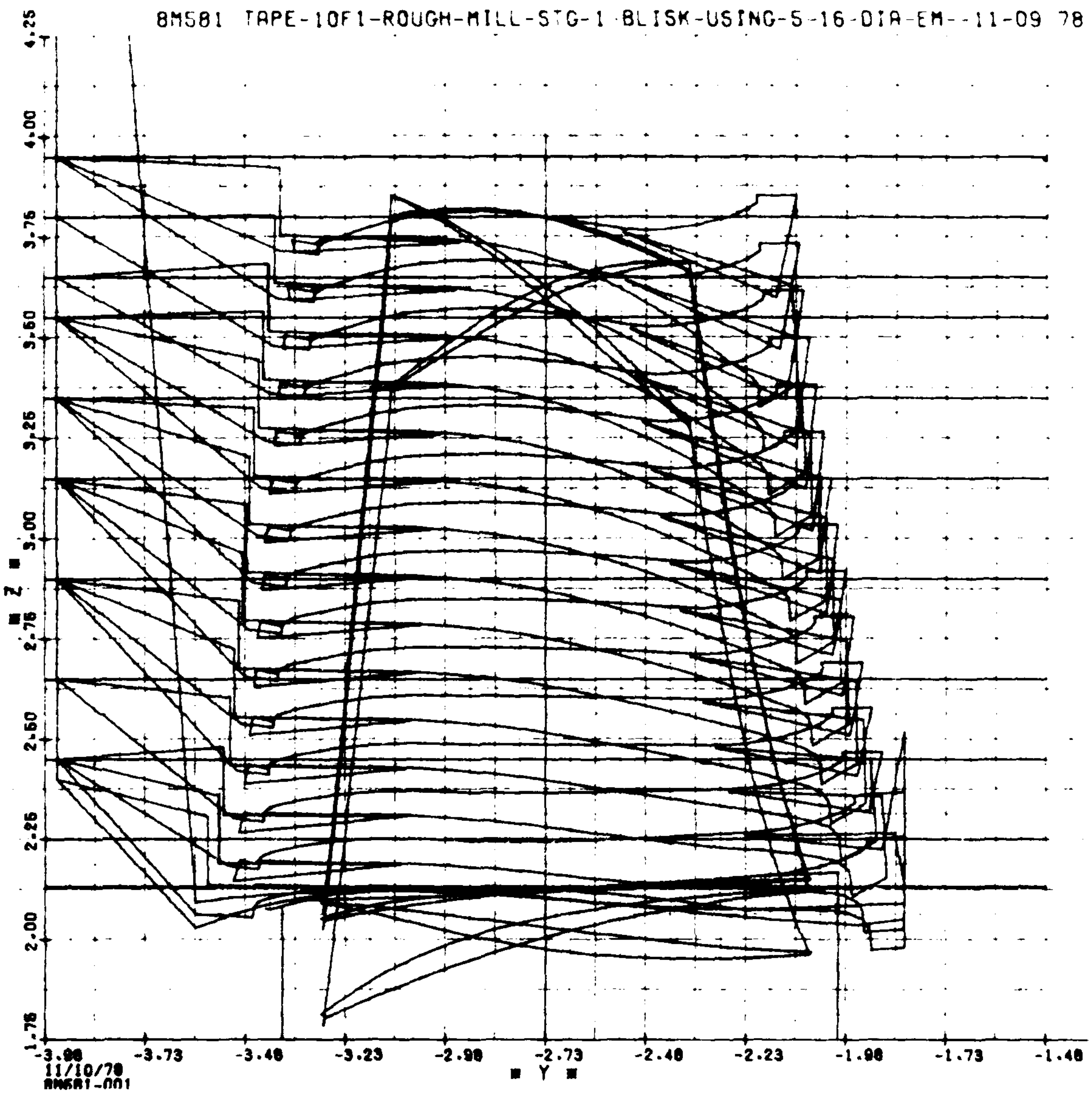



Figure 21. Computer Plot of Tool Paths to Rough Mill a Pocket for Stage 1 Blisk.

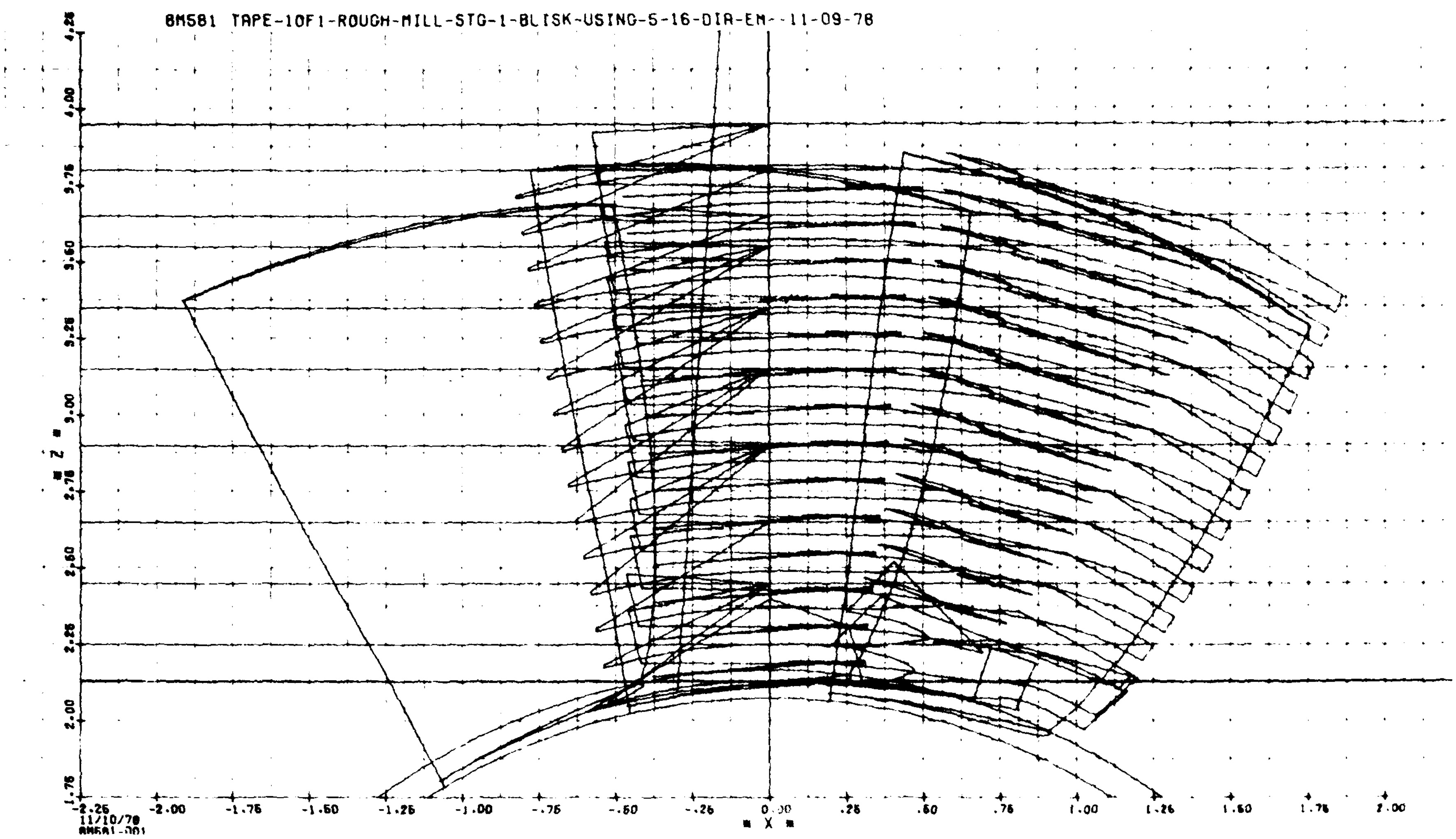



Figure 22. Computer Plot of Tool Paths to Rough Mill a Pocket for Stage 1 Blisk.

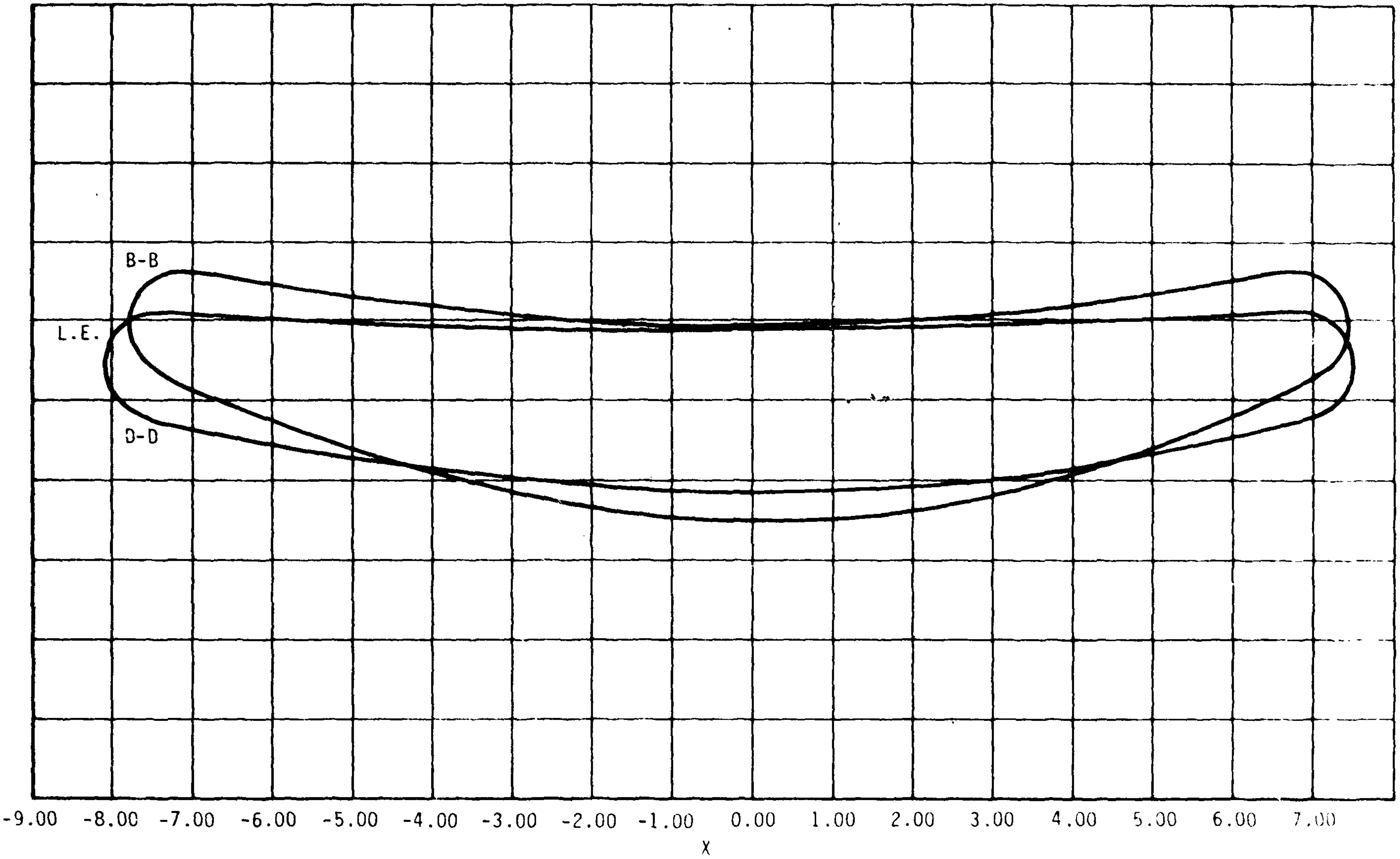



Figure 23. Computer Plot of Stage 1 Blisk Glass Layouts for Sections BB and DD.

| RADIUS AA | AXIAL LOCATION AC |
|---|---|
| 2.1010 | .100 |
| 2.1036 | .200 |
| 2.1077 | .300 |
| 2.112 | .400 |
| 2.118 | .500 |
| 2.1515 | 1.000 |
| 2.1575 | 1.100 |
| 2.1625 | 1.200 |
| 2.1665 | 1.288 |

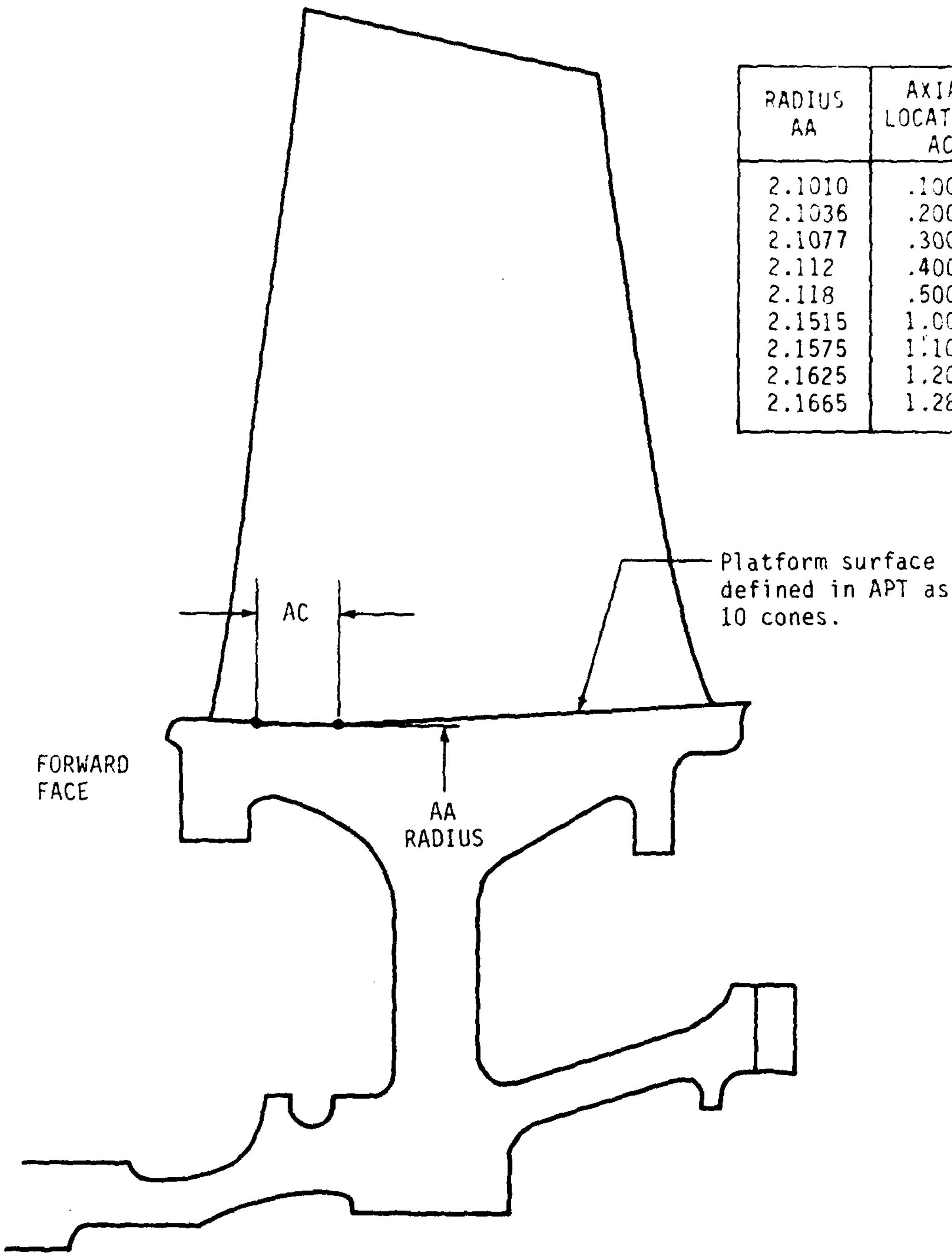



Figure 24. Stage 1 Blade With Platform.

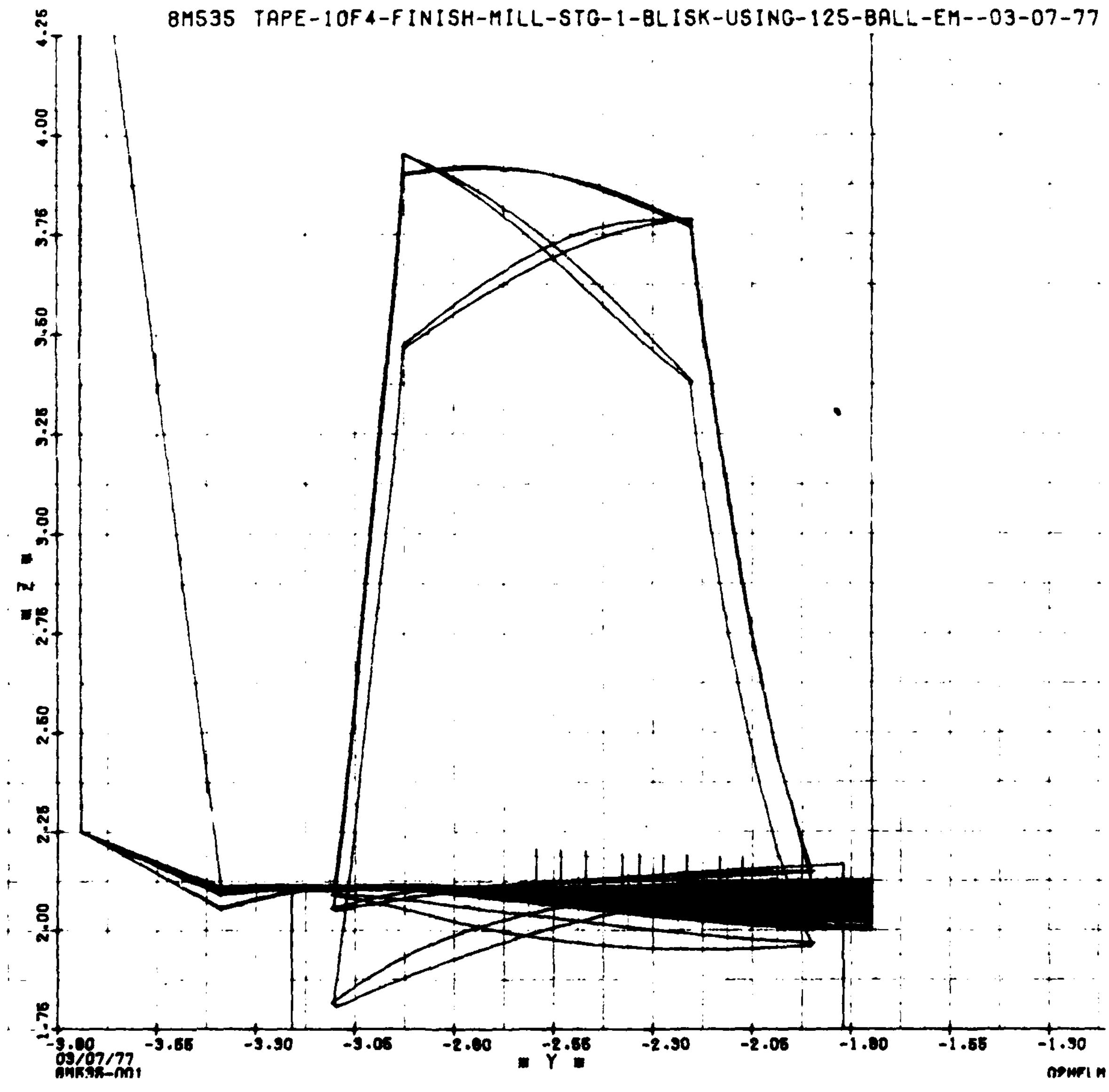



Figure 25. Computer Plots of Tool Paths to Finish Machine Platform.

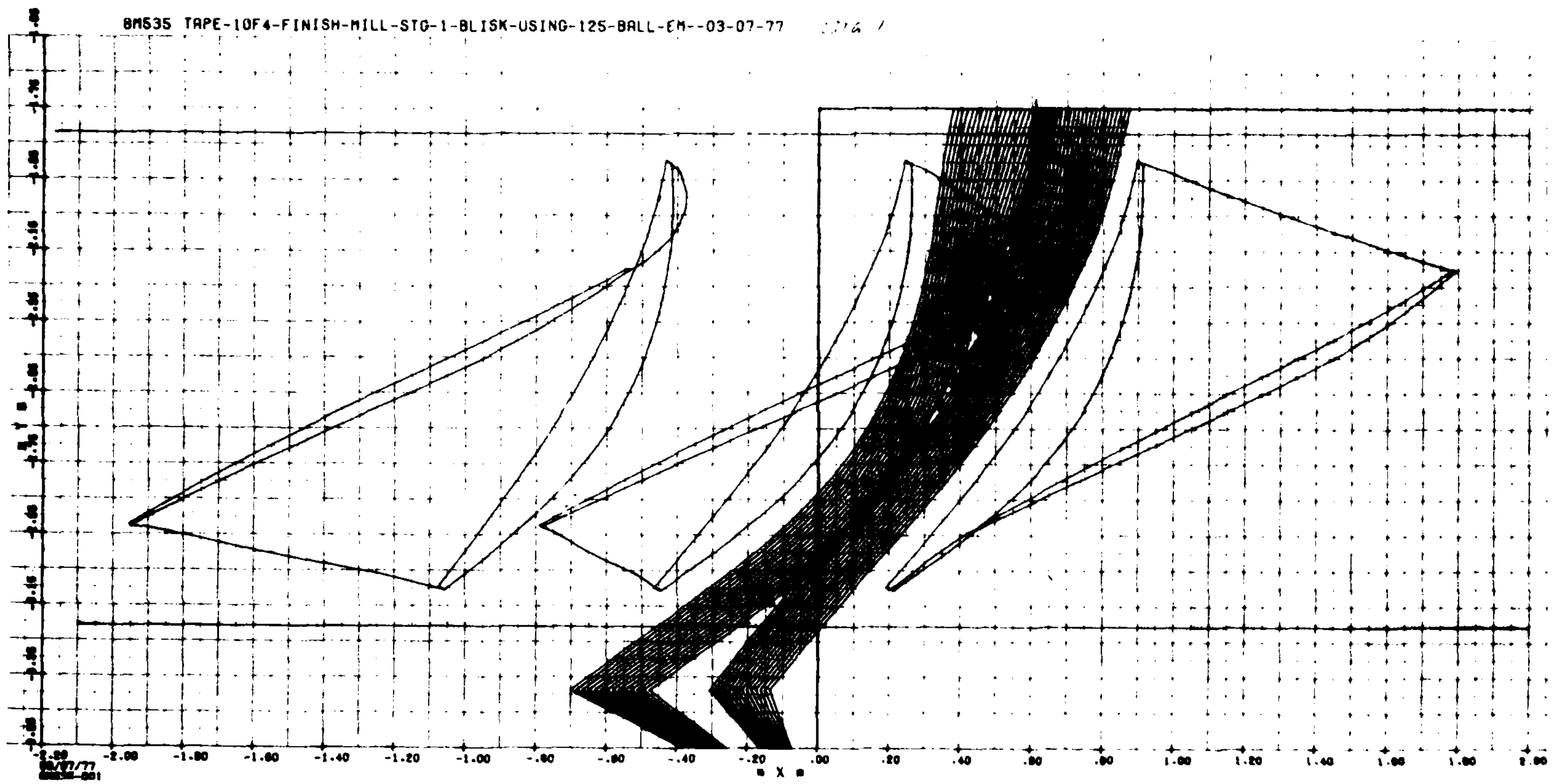



Figure 26. Computer Plot of Tool Paths to Finish Machine Platform.

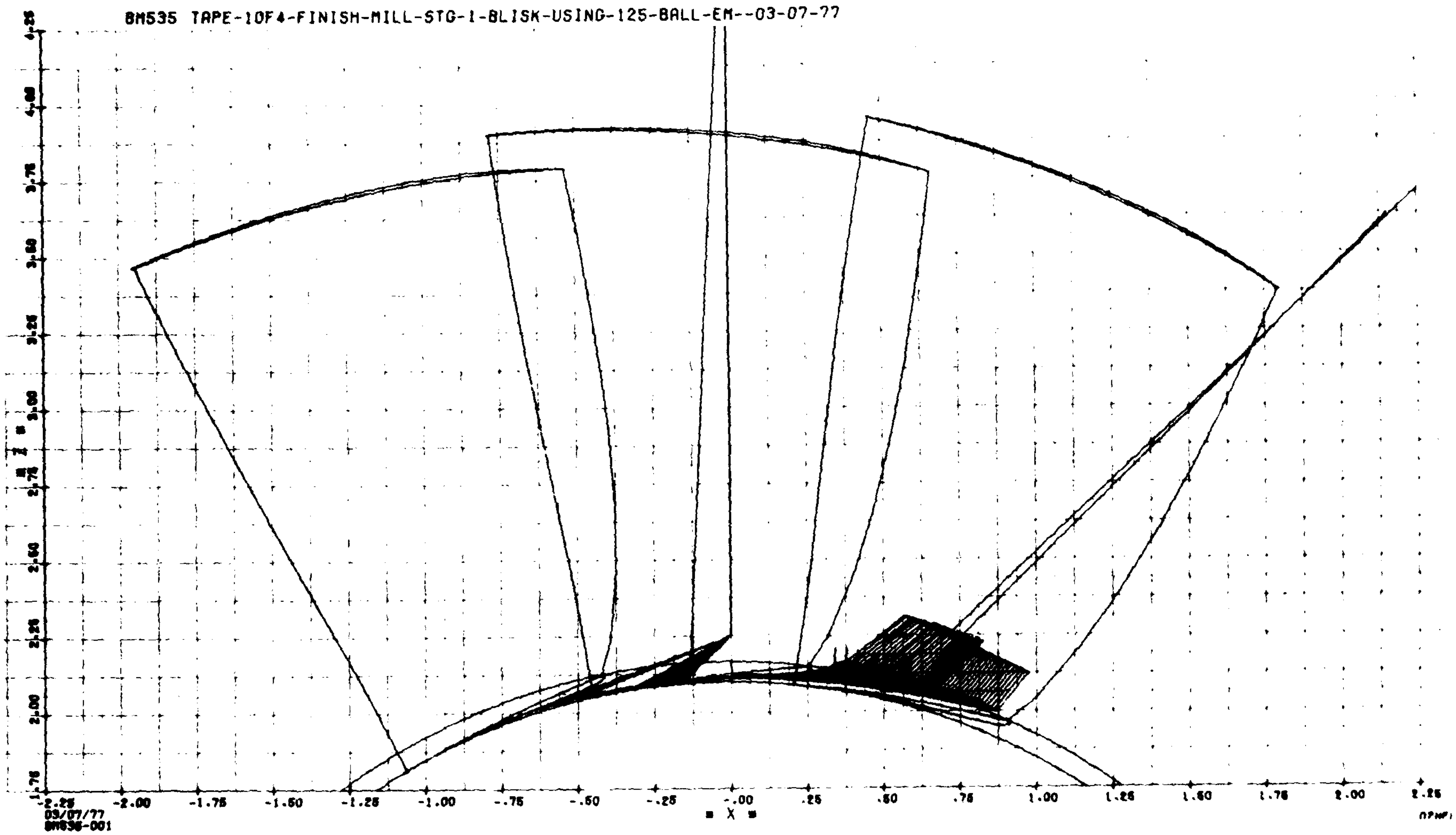



Figure 27. Computer Plot of Tool Paths to Finish Machine Platform.

Figure 28. Contour Milled Airfoil Simulated Blisk.

NUMERICAL-CONTROL PROGRAMMING
FOR
IMPELLER

## NUMERICAL-CONTROL PROGRAMMING FOR IMPELLER

### INTRODUCTION

The numerical control (NC) programming needed for impeller milling presented a unique challenge due to the complex shape of this engine part. The principal reasons for the challenging effort were:

1. The application of the APT system was considered to be impractical for this part.
2. Although the GEMESH system was suitable for handling the milling for a general sculptured surface, its application to NC programming of the impeller did not progress at a sufficiently rapid pace to satisfy project schedules.
3. It was decided to parallel GEMESH programming with HECTRAN system programming.
4. The impeller required the use of all five axes on the milling machine.

The various requirements, imposed by the NC programming of the impeller, are described in detail in this section. Other topics covered are: the procedure used in part programming with the GEMESH system; tryouts performed with GEMESH; a discussion of problems and solutions encountered with GEMESH; part programming using the HECTRAN system; a summary of problems and solutions relative to HECTRAN; and a brief discussion of the distributed numerical control (DNC) system used in numerical control of production milling machines.

### GEOMETRIC DEFINITION OF THE IMPELLER

A geometric definition of the impeller exists as a data base in a file in the General Electric computer center. This data base was created by Engineering for design and stress analysis and for solving aerodynamic problems. The blade contour coordinates, listed on the drawing (see Figure 29, pg 63) were derived from the Engineering data base. However, both the data base and the coordinate table are not in a suitable format for the APT part programming. It was, therefore, necessary to consider the manner in which the machining of the impeller would be programmed and the most suitable geometric format.

The impeller blade hub contour is defined by a table of coordinates for the S and T dimensions as shown in Figure 30 (pg 64). The first task involved the definition of this contour in APT. It was evident that the APT sculptured surface features were limited. Therefore, the General Electric, Aircraft Engine Group in Evendale, Ohio, and Honeywell, Phoenix, Arizona were contacted to determine if there were any improvements which could be applied to the impeller. It was found that sculptured surfaces could not be applied in this case.

### CHOICE OF GEMESH COMPUTER SYSTEM

The GEMESH computer system was the first choice for part programming of the impeller. This system was created by the General Electric Aircraft Engine Group, in Evendale, Ohio, to solve the problem of milling free-form surfaces, such as airfoils, within tolerance. Although the APT system is capable of handling parts whose surfaces are comprised of planes, cylinders, cones and spheres, it cannot accommodate a general sculptured surface. GEMESH was designed to fill this void and is capable of handling surface geometry that is too complex for the APT system.

CHOICE OF GEMESH COMPUTER SYSTEM - Continued

It consists of five major process areas, each having a specific key functions. These are as follows:

1. Surface definition
2. Surface boundary definition.
3. Cutting of boundaries.
4. Cutting of surface.
5. Generation of cutter location data file.

## Part Programming Using GEMESH

The Design Engineering data base, for the impeller blades, was entered into the GEMESH system and a surface was fitted through the points that represented the side of one blade (see Figure 31, pg 65). However, before the GEMESH system can be used for programming of the machining of a given surface, it is necessary to define a closed surface curve consisting of four segments. This data base was furnished by Design Engineering and placed into an APT binary data file.

A cutter path sequence, was generated using a 1/8 inch-diameter ball cutter with a 0.025-inch step-over. This created a tool centerline (CL) path and tool axis vectors.

By using APT and FORTRAN programs, a GEMESH data file of the hub (blade platform) was created. This provided a GEMESH surface of the hub (Figures 32-33, pgs 66-67). A cutter path sequence using a 5/16-inch-diameter end mill was generated for rough cuts for a portion of the hub. This indicated that the original end mill could not generate the desired surface and a 5/16-inch-diameter ball cutter was necessary for this part of the impeller.

For convenience in describing the machining of the impeller, it was divided into three areas, as follows:

Area A - The uniform slots between vanes at the discharge end of the impeller that can be machined with a 5/16-inch-diameter end mill.

Area B - The L-shaped section at the inlet end of the three vanes of different lengths that can be machined with a 5/16-inch-diameter end mill.

Area C - The restricted area between vanes that requires a 3/16-inch-diameter end mill.

Refer to Figure 34 (pg 68) for a pictorial display of the above areas.

Areas A and B require five GEMESH surface definitions for machining. Figure 35 (pg 69) shows these five surfaces. The boundaries for these surfaces were the hub (platform) surfaces, the discharge end of the airfoil, and the leading edge.

CHOICE OF GEMESH COMPUTER SYSTEM - Continued

The GEMESH system is capable of creating cutter paths for only one surface at a time. Five different programs were therefore generated for each surface, using a 5/16-inch-diameter end mill and leaving 0.015-inch-thick stock for a finish cut on the simulated airfoil.

The next step was to combine the individual programs so that the resulting program produced an efficient cutter path which would machine all five surfaces with one cutter and one tape. To accomplish this, the GEMESH programs had to output APT CL data magnetic tapes; these tapes were then combined into one continuous CL tape.

A FORTRAN version of a CLEDIT program was used to combine the five CL tpaes into a single tape. The resultant tape was then postprocessed for the New England 5-axis machine.

## GEMESH Trials

During an evaluation of the postprocessed output of the rough machining program, for Areas A and B, two potential problems were revealed. The first was that the tool axis angle changed drastically between cuts, which would result in a poor surface. This problem was resolved by modifying the tool axis angles in the programs.

The second problem was that the tool approach path, from the approach point to the workpiece, did not clear the fixture. This was resolved by making the tool travel from the approach point to an intermediate point, at which point it cleared the fixture, and then to the workpiece. To arrive at this intermediate point in the program, it was necessary to transfer the point from the New England Machine coordinate system to the GEMESH system and tool axis vector input data. This was done by applying the machine class equations, i.e., the mathematical equations which convert the part coordinates into the machine coordinate system. This data was then incorporated into the program and a new machine control tape was generated.

A CL tape to rough machine Area C of the impeller blade was created next. In order to have the 5/16-inch-diameter end mill cut this area at a 45-degree angle in the machine system, it was necessary to rotate and translate the GEMESH data and fences (boundaries) to give optimum GEMESH machining surfaces. The CL tapes for rough machining the impeller hub in areas A and C were also created. These tapes remove stock to within 0.015 inch of the finish dimension with the roughing cutter making a 0.07-inch step-over between cuts.

Finally, a finishing tape was programmed to machine the trailing airfoil surface of the simulated impeller. This used a 3/16-inch diameter ball mill which starts at the air exit edge of the blade and feeds down in 0.01 inch steps to the hub (refer to Figure 36, pg 70). The paper tape length to machine one side of the blade was 1125 feet long.

A part program was also required for the fillet between the airfoil surface and the impeller hub. The radius of curvature for the fillet was set at 0.12 inch by the engineering drawing. The part program involved the fitting of a GEMESH surface between the airfoil and hub surfaces, to provide for the fillet.

CHOICE OF GEMESH COMPUTER SYSTEM - Continued

An updated engineering data base, for one side of a blade, was entered into the GEMESH system, to fit a surface through the data points. The surface generated was better than any produced prior to this test; however, it showed some roughness in certain areas. This was considered to be due to the fact that GEMESH is very sensitive to slope reversals in curves and tends to exaggerate them. The section data was once again entered into an APT tabulated cylinder (TABCYL) and the curves examined for any slope reversals. All points which contributed to the slope reversals were eliminated. The data was then re-run through the APT TABCYL program to verify slopes. This was done for all sections of the blade. In addition, the data base was put into the GEMESH system with a YZ rotation of 90 degrees. These changes eliminated the above effect as well as the excessive plunge cuts which were evident during earlier tryouts.

A new roughing tape for Area A was prepared, following the above tryout. This tape was programmed with a feed rate of 6 inches/minute and a downfeed of 0.060 inches. In addition, an optional stop was inserted after each pass. This allows the machine operator, during process development, to stop the machine after each cutting pass.

The above tape was tried out on the New England machine by machining three adjacent pockets. The tryout confirmed that the feeds and depth of cut were correct. The tryout also showed that the cutter left cusps on the surface of the leading wall of the airfoil. This is normal and was to be expected. However, the trailing wall of the airfoil had no cusps whatsoever, indicating that the tool clearance angle was too small and that undercutting had resulted. The clearance angle was modified in the program and a new tape was generated.

The new roughing tape for Area A was next used for machining three adjacent pockets, following which the airfoils were traced and compared with the master glass layouts. The inspection verified that the problems identified in earlier tryouts had been resolved. However, some new problems were identified. These were that the airfoils were 0.075 inch too thick, the locations of the surfaces were incorrect, and that insufficient clearance tool angle had been used. To correct these problems, new tapes were generated and tried out. Inspection of the test piece showed that the roughing in Area A was successful and produced geometry much closer to design requirements than previous tapes.

In programming for the rough machining of Area B, it was decided to keep the number of milling machine axes to a minimum. Consequently, the roughing of this area was first limited to four axes. However, the tryouts showed that, without the use of the 5th axis, the tool holder would hit some parts of the airfoils. Accordingly, a tape using all five axes was generated. Although this showed an improvement over the 4-axis approach, the tryouts showed that the program did not control the A-axis movements correctly. Further evaluation of the situation suggested that a 4-1/2 axis approach be taken; 4-1/2 axis is defined as complete freedom of movement of the A axis. In this particular instance, the A-axis was held rather close to 345 degrees.

A tape was generated which reflected these conditions and three Area B airfoils were successfully rough-machined.

CHOICE OF GEMISH COMPUTER SYSTEM - Continued

When machining Area C, the stock existing between Areas A and B is removed. Based on the experience with Area B, the Area C program was created in a 4-1/2 axis configuration. In this program, the A-axis was held relatively constant at 320 degrees. One set of blades was machined (a set of blades consists of a full airfoil, the first splitter and the second splitter, see Figure 34, pg 68). The machined airfoils were traced and compared with the master layouts. Results showed relatively good conformance to design, and were used in improving the program.

New fence data was generated for entry into the hub GEMESH programs. Using this data, a hub rough machining tape for Area A was created. The airfoil roughing tapes for area A were also modified to include feeds and speeds which were planned for the production NC milling machine.

In anticipation of impeller cutting characteristics being similar to those experienced in the blisk development milling project, a program was written and tapes generated to measure cutter deflection when milling INCO 718 material. Both 3/16-inch-diameter and 1/8-inch-diameter cutters were programmed to gather data for incorporation in the impeller program. It was expected that this would result in fewer iterations of tape tryouts than was experienced with blisks.

GEMESH Problems and Solutions

The Engineering data for the trailing surface of the impeller was merged into a GEMESH data file which created a surface through the data. Initial verification of this surface by computer plots indicated a discontinuity problem.

To verify the input data, an APT TABCYL was generated through the data of one section of the airfoil. Analysis of the APT output revealed that, at some local spots, the curvature and slope of the data deviated from the overall surface. Although the data was sufficiently accurate for the various computerized analyses programs used by Design Engineering, the tolerance used in their computer data base was too wide to be acceptable to the GEMESH system.

In fact, the extrapolation of the data, which GEMESH performs, causes the sharp surface discontinuities shown in Figure 37 (pg 71).

In an effort to resolve the above problem, two new sets of airfoil data, defining one side of a blade, were prepared by Engineering. One set defined each surface point more precisely (to eight decimal places). The other set defined the surface with fewer points (only one quarter of the number of points originally used). An APT TABCYL was then fitted through each set of the data nad the smoothness of the curves was checked. This indicated that the extra precision did not help, but the wider spacing in the data points was promising.

A tape to rough machine a test blank was generated. Tryouts of the tape showed that the above problem was eliminated. However, the test tape was made with estimated cutting parameters which were optimistically biased. Tryouts showed that the downfeed and feed rates were too great and tool breakage occurred. A closer study was made of the cutting parameters and a corrected tape was generated.

CHOICE OF GEMISH COMPUTER SYSTEM - Continued

As work continued on part programming with GEMESH, machind tryouts of one of the trial tapes, for roughing the impeller with a 5/16-inch-diameter cutter, were conducted. A test piece and the holding fixture were loaded on the New England 5-axis machine. This verified that the fixturing was designed correctly. Machining of the test piece involved rough-machining of the pocket between two full blades. Examination of the test piece revealed that the tool axis angle was incorrect in some locations which tended to make the cutter plunge cut instead of performing a side cut. Modifications were made to the tape to correct this problem.

The airfoil roughing tapes for Areas A, B, and C, which were modified earlier, were tried out on a steel blank and an INCO 718 forging blank. In general, the tryouts were satisfactory. The exception was when the cutter retracted at the end of a cut near the hub in Area C. In this situation, the cutter milled a portion of the adjacent blade. The program was changed to keep the A-axis close to 350 degrees instead of 315 degrees which was the previously used value.

Later in the project, tool breakage was experienced during tryouts of the rough machining tapes. It was determined that the end of the cutter was not engaged in cutting over a full 180 degrees around its circumference. Changes were made in the cutter down feed step milling to correct the problem. These changes involved staggering the depth of cut as the cutter moves from one side of the airfoil to the next.

Additional tryouts also showed that excessive material was being removed from the impeller hub surfaces. This problem was corrected by making appropriate changes in the program.

Although solutions were found for each of the problems encountered with GEMESH, the time required to identify and solve problems slowed programming progress. In an effort to assure that continued problems with GEMESH would not delay project completion, a parallel programming effort was undertaken; HECTRAN was selected for this effort. Progress with HECTRAN was so good that GEMESH programming was discontinued, so that impeller programming could advance as rapidly as possible.

PART PROGRAMMING USING HECTRAN

The HECTRAN programming language was developed by Intratec, Inc., specifically for NC programming of impellers. It was designed for use with a Prime computer.

A Prime computer was conveniently available for programming work, and the installation of a Prime computer in the GE Lynn, Massachusetts plant was in progress, assuring future availability.

Initial tryouts with a trial tape showed that the HECTRAN system was capable of successfully controlling the New England machine during simultaneous 5-axis milling of an impeller blade. Following these tests, rough and finish machining tapes were generated for all three blades and the hub surface of the impeller using HECTRAN. In addition, a separate tape was produced for machining the blade leading edges. These tapes were then tested on the development milling machine while milling an INCO 718 impeller blank. HECTRAN could only machine streamlines as shown in Figure

CHOICE OF GEMISH COMPUTER SYSTEM - Continued

38 (pg 72). The HECTRAN programming system had to be modified by Intratec to provide the capability of machining with a constant width of cut equidistant from the hub (Figure 39, pg 72). The results of this tryout showed a need for program modifications due to cutter breakage. It was determined that this was caused by the fact that the cutter tip was not engagedover a full 180 degrees while cutting.

New tapes were generated to provide a staggered depth of cut as the cutter moved from one side of the airfoil to the next. These tapes represented a major improvement and made possible further programming refinements. To derive the necessary data, individual cutter paths, for the worst areas, were observed and measured on an impeller blank. The milling machine operator adjusted the depth of cut by manually overriding the tape and by adjusting the machine Z-axis up or down, there by obtaining acceptable cut geometry. The object was to keep the cutter tip below the adjacent path and not more than 0.070 inch below the previous cut on the same side.

The HECTRAN tapes were then manually modified to include these data. Additional passes, where heavy cutting occurred, were also included. These tapes were tried on the development machine, and were successful on an INCO 71 impeller blank.

Upon completion of these tests, a hub roughing and a fillet finishing tape were generated in HECTRAN. The hub roughing tape was based on the use of a 3/16-inch-diameter end mill for removing material left by the section roughing tapes and for milling the hub contour to a more uniform envelope for the hub finishing tapes. The fillet finishing tape was generated for the large splitter blade, to check out compatibility with the blade and hub finishing tapes.

A total of 19 different tapes were ultimately produced for NC machining of the impeller. These included the above tapes, a blade roughing tape, a tape for the main vane leading edge profile, and three fillet tapes. All of these tapes were lated modified to be compatible with the production milling machine.

## HECTRAN PROGRAMMING PROBLEMS AND SOLUTIONS

During the rough machining of the first production part, tool breakage occurred in the narrow passages using the 3/16-inch-diameter cutter. This problem was caused by excessively large downfeed of the cutter which produced excessive cutting force. Manual changes had to be made to the production tapes since the necessary changes are beyond the present capability of the HECTRAN system.

It was observed that the finishing cutters were deflecting 0.003 inch during vane finish milling. Accordingly, a new set of vane finishing tapes were produced to compensate for the deflection. The tapes ran successfully on the development milling machine.

HECTRAN PROGRAMMING PROBLEMS AND SOLUTIONS - Continued

Two different trial programs were generated by new modifications to the HECTRAN processor. The goal was to keep the cutter tip buried at least 0.030-inch into the material 180 degrees around the forward direction of the cutter motion. However, it was found that the 3/16-inch-diameter cutter should not exceed a 0.070-inch depth of cut along the blade side of the cut by any significant amount or it would break. The curvature and twist of the impeller made this task extremely difficult to accomplish within the program. A tryout of these two tapes proved that more work was required on the HECTRAN processor, if the desired cut geometry was to be achieved.

The HECTRAN data base for the geometry of hub low path surfaces was defined with additional coordinates. An analysis indicated that newly defined geometry should not deviate from design nominal by more than about 1 mil. Analysis also indicated that the data base previously used could produce deviations of several mils from design nominal. This improvement was expected to significantly increase conformance of milled hub geometry to design limits.

Later in the project, it was noted that the engineering data, which defined the impeller airfoil, had minor "ripples" in it. The manufacturing process magnified these "ripples" and produced an unsatisfactory surface which required local benching. To eliminate this problem, a cubic spline fit routine was added to he HECTRAN system for impeller NC programming. The new routine modifies the engineering data points within a small tolerance band, to provide a smoother blade surface. Machining tapes, incorporating this routine, were generated for the main vane and produced satisfactory results.

The two splitter vanes were then machined with tapes produced using this smoothed data. Since all cutter paths are influenced by the blade airfoil data, including those that finish the hub surface between vanes, it became profitable to make new hub finishing as well as fillet finishing tapes to get the best possible surfaces.

After additional modifications to the HECTRAN system, it became possible to profile the leading edges of all three blades and then round them. Profiling consists of cutting the leading edge to its proper length perpendicular to the sides by passing the cutter down from the shroud to the hub in one continuous motion. Rounding moves the cutter from one side of the blade to the other while generating a radius around the edge in continuous down-steps to finally blend with the fillet at the hub.

Another enhancement added to HECTRAN allowed the milling of the hub area to be extended beyond the main vane to include the area ahead of the vane all the way to the curvic coupling to eliminate turning and blending in this difficult area.

## DISTRIBUTED NUMERICAL CONTROL SYSTEM

The distributed numerical control (DNC) system is based on the use of a computer, with a large memory capability, to store many NC programs and, hence, eliminate the need for long punched paper tapes for numerical control of production milling machines. It is interesting to note that the length of the tapes involved in NC miling of a Stage 1 blisk blade is about 1 mile. The Interdata 7/32 computer, which runs the DNC system at the General Electric blisk and impeller production facility in Hooksett, New Hampshire, is capable of storing all of the programs for milling blisk and impeller airfoils, as well as programs for other operations performed on lathes. The DNC system can drive many milling and lathe machines simultaneously. The system permits independent control of each machine.

A package of control cards for the Honeywell computer was developed. The tape that mills the test blocks on the milling machine was run against this control package and a magnetic tape generated. This tape included unique codes required for the machine operator's cathode ray tube display control terminal. The tape was tried in the Hooksett N.H. blisk production facility and was found to be compatible with the DNC system.

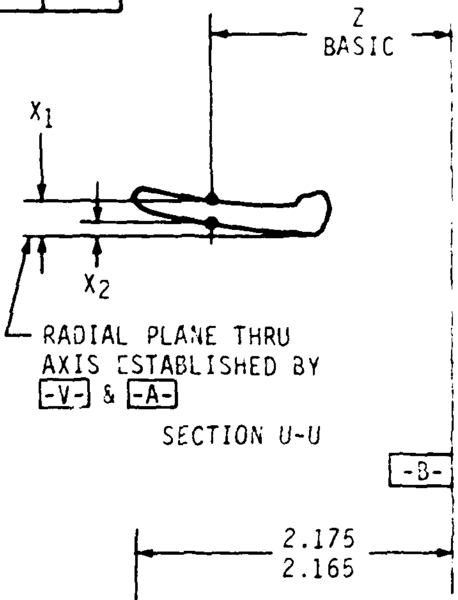
Provision was made in the magnetic tapes for the DNC system to search for necessary pick up points whenever a re-start is required due to any type of failure. Later, software was generated to enable the Hooksett computer to directly access a file on the Honeywell 6080 computer at the General Electric, Lynn, Mass., plant.

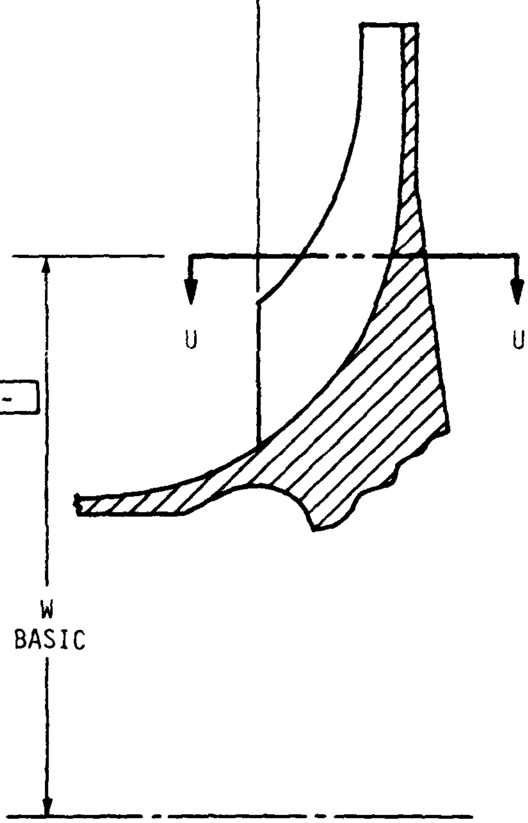
| W | Z | $Y_1$ | $Y_2$ | $X_1$ | $X_2$ |
|---|---|---|---|---|---|
| 1.80 | 3.27 | .6915 | .6521 | | |
| | 3.07 | .4979 | .4491 | | |
| | 2.97 | .4196 | .3673 | | |
| | 2.87 | .3517 | .2963 | | |
| | 2.77 | .2930 | .2347 | | |
| | 2.67 | .2400 | .1814 | | |
| | 2.57 | .2003 | .1357 | | |
| | 2.47 | .1642 | .0970 | | |

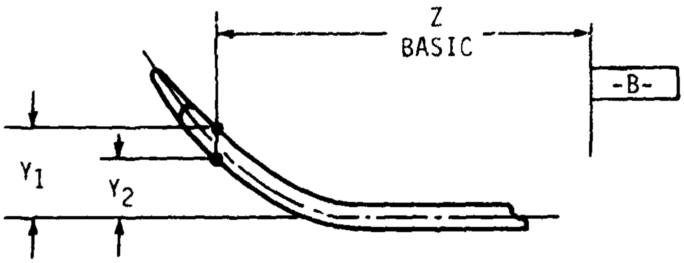
| W | Z | $Y_1$ | $Y_2$ | $X_1$ | $X_2$ |
|---|---|---|---|---|---|
| 1.90 | 3.27 | .7265 | .6918 | | |
| | 3.17 | .6173 | .5767 | | |
| | 3.07 | .5224 | .4772 | | |
| | 2.97 | .4118 | .3908 | | |
| | 2.87 | .3631 | .3159 | | |
| | 2.77 | .3061 | .2510 | | |
| | 2.67 | .2531 | .1943 | | |
| | 2.57 | .2880 | .1463 | | |
| | 2.47 | .1699 | .1059 | | |
| | 2.37 | .1332 | .0710 | | |

| W | Z | $Y_1$ | $Y_2$ | $X_1$ | $X_2$ |
|---|---|---|---|---|---|
| 2.90 | 2.47 | .2252 | .1956 | | |
| | 2.37 | .1766 | .1437 | | |
| | 2.27 | .1367 | .1007 | .1286 | .1169 |
| | 2.17 | .1047 | .0659 | .0908 | .0798 |
| | 2.07 | .0776 | .0381 | .0683 | .0495 |
| | 1.97 | .0607 | .0164 | .0521 | .0250 |
| | 1.87 | .0471 | .0003 | .0410 | .0057 |
| | 1.77 | .0376 | .0126 | .0340 | .0090 |
| | 1.67 | .0314 | .0213 | .0298 | .0198 |
| | 1.57 | .0270 | .0270 | .0270 | .0270 |
| | 1.47 | .0269 | .0269 | .0276 | .0276 |

| W | Z | $Y_1$ | $Y_2$ | $X_1$ | $X_2$ |
|---|---|---|---|---|---|
| 4.00 | 1.57 | -.1750 | -.2166 | -.1750 | -.2166 |
| | 1.47 | -.1728 | -.2188 | -.1727 | -.2189 |
| | 1.37 | -.1703 | -.2207 | -.1707 | -.2209 |




RADIAL PLANE THROUGH AXIS
ESTABLISHED BY -V- & -B-

NOTE:
REFER TO DRAWING 6035T18
FOR MORE DETAILS.

Figure 29. Example of the Coordinate Matrix Which Defines the Blade Geometry.

| T | S |
|---|---|
| 1.9493 | 3.8539 |
| 1.9322 | 3.7576 |
| 1.9178 | 3.6613 |
| 1.9062 | 3.5650 |
| 1.8978 | 3.4686 |
| 1.8926 | 3.3723 |
| 1.8908 | 3.2760 |
| 1.8918 | 3.1700 |
| 1.8947 | 3.0700 |
| 1.9143 | 2.8700 |
| 1.9576 | 2.6700 |
| 2.0281 | 2.4700 |
| 2.1317 | 2.2700 |
| 2.1971 | 2.1700 |
| 2.3701 | 1.9700 |
| 2.6046 | 1.7700 |
| 2.7124 | 1.6944 |
| 2.8698 | 1.5856 |
| 3.2737 | 1.4110 |
| 3.5531 | 1.3591 |
| 3.7290 | 1.3444 |
| 3.9514 | 1.3320 |
| 4.1612 | 1.3261 |
| 4.3671 | 1.3208 |
| 4.5698 | 1.3190 |
| 4.6617 | 1.3190 |

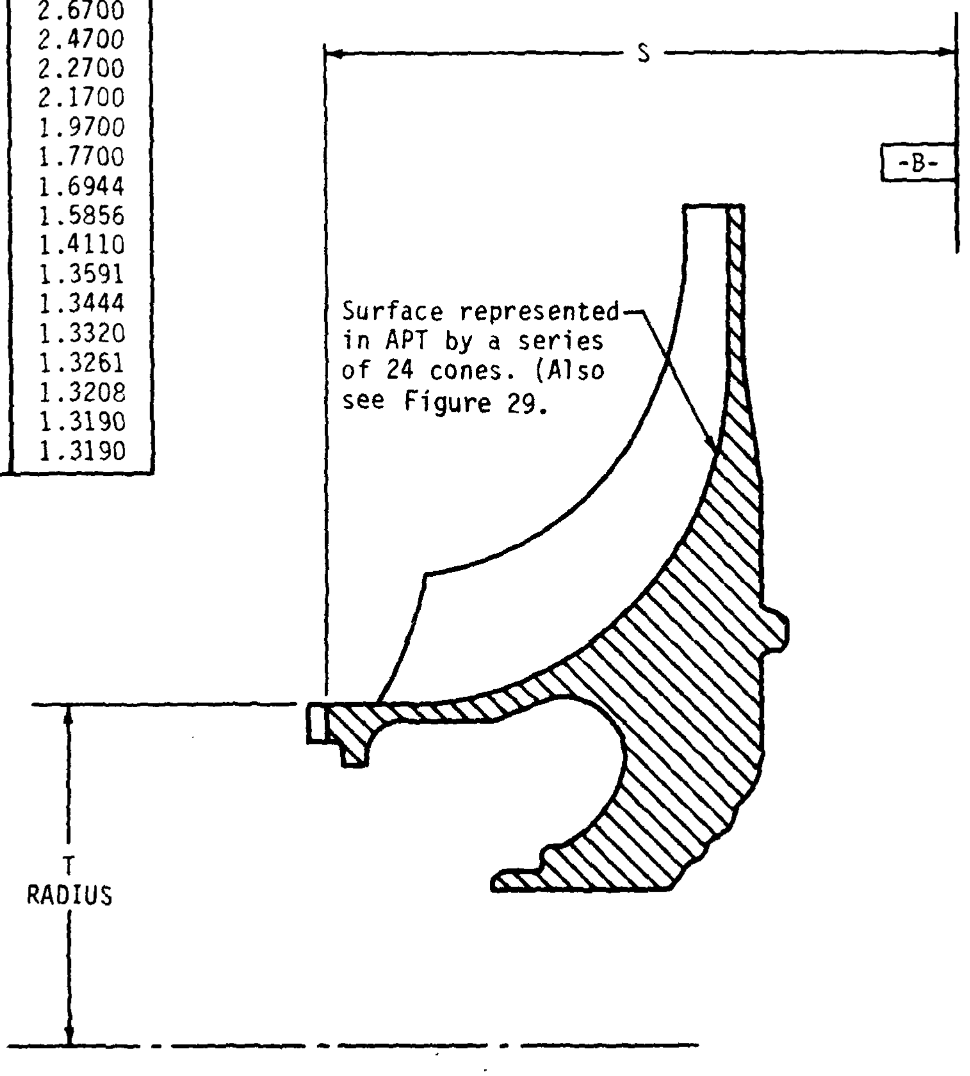



Figure 30. Coordinate Table Which Defines Blade Hub Contour.

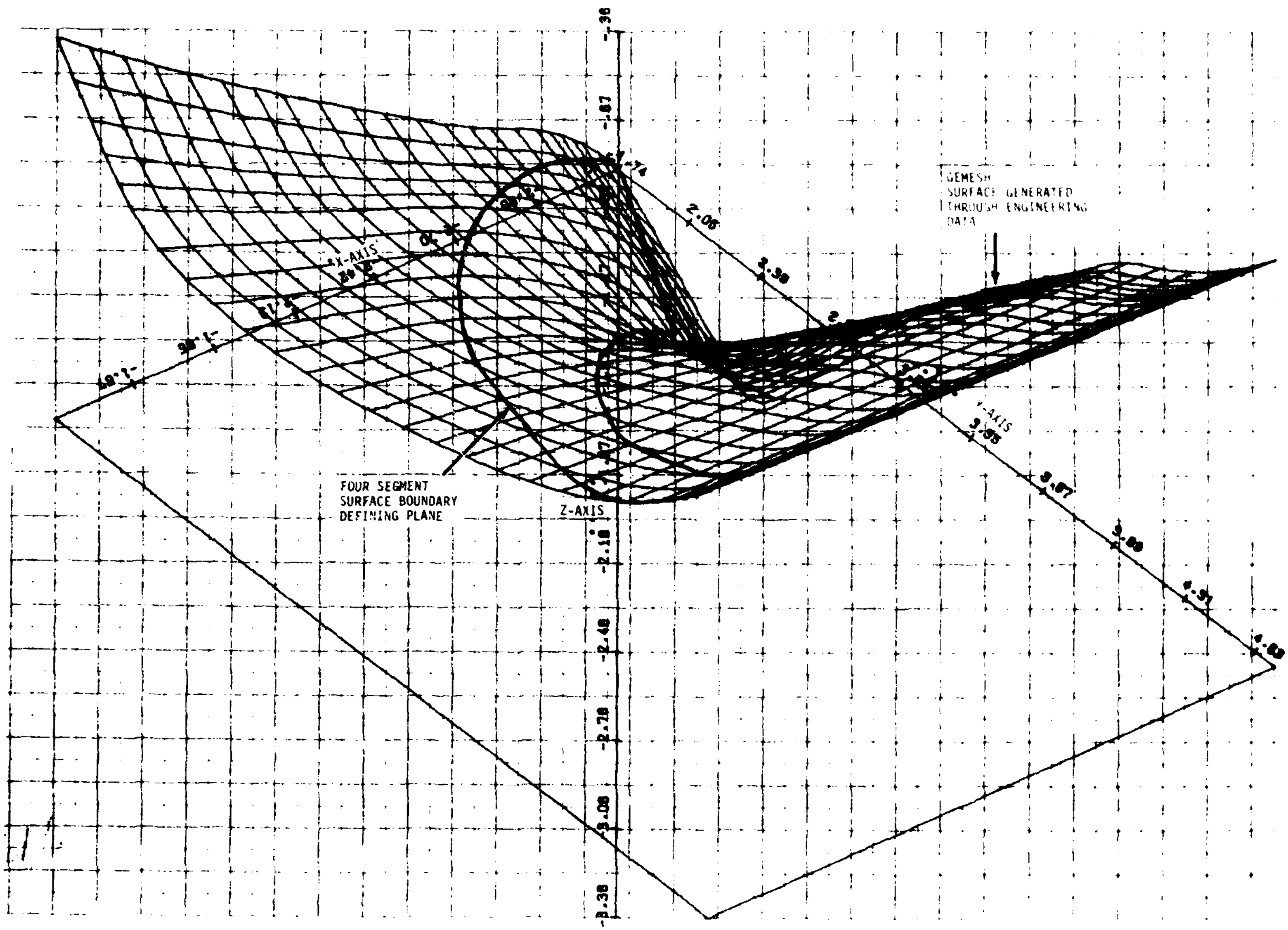



Figure 31. Computer Plot of GEMESH Generated Surface of Impeller Blade.

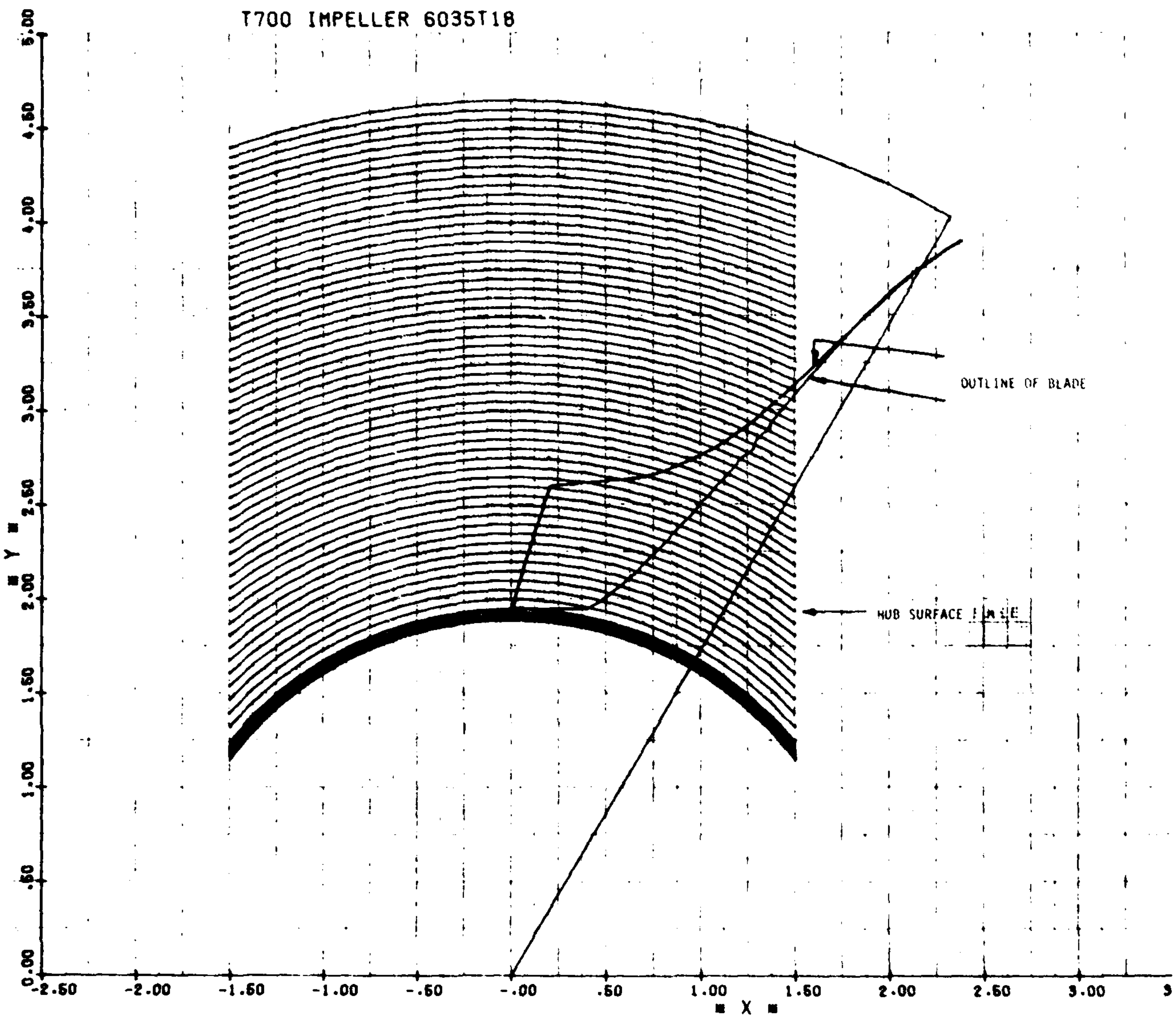



Figure 32. Computer Plot of GEMESH Generated Surface of Impeller Hub.

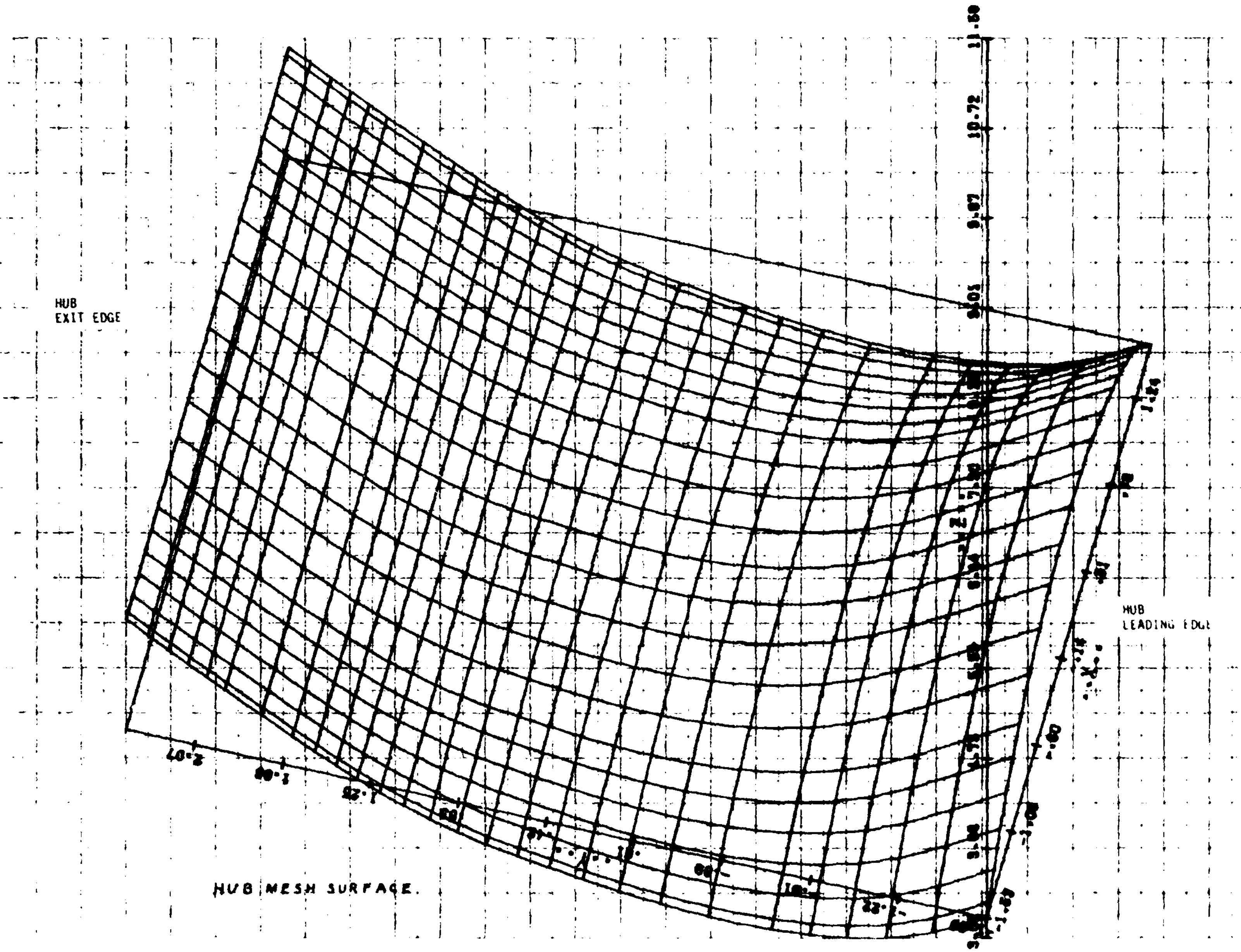



Figure 33. Computer Plot of GEMESH Generated Surface of Impeller Hub.

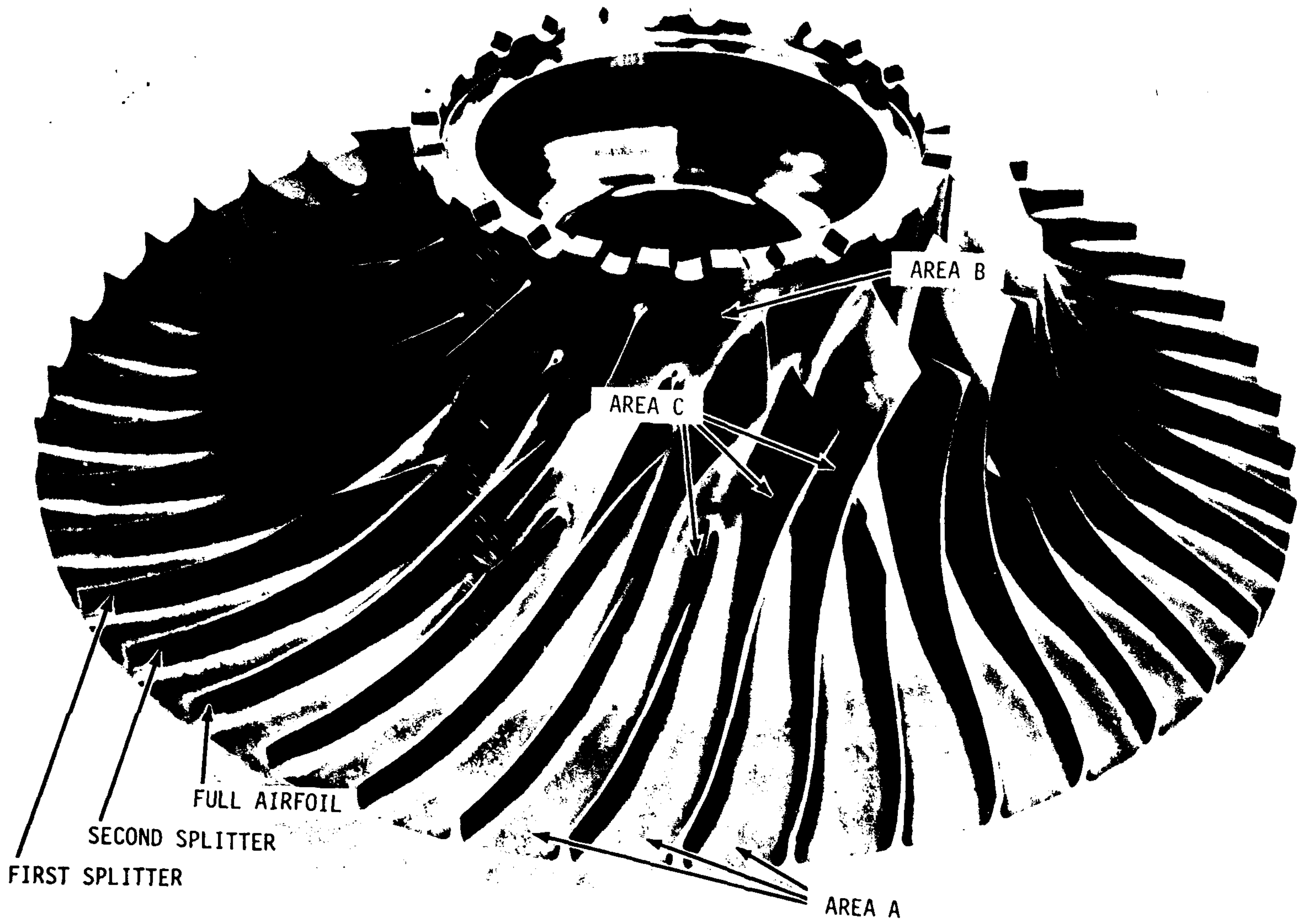



Figure 34. View of Impeller Machining Areas.

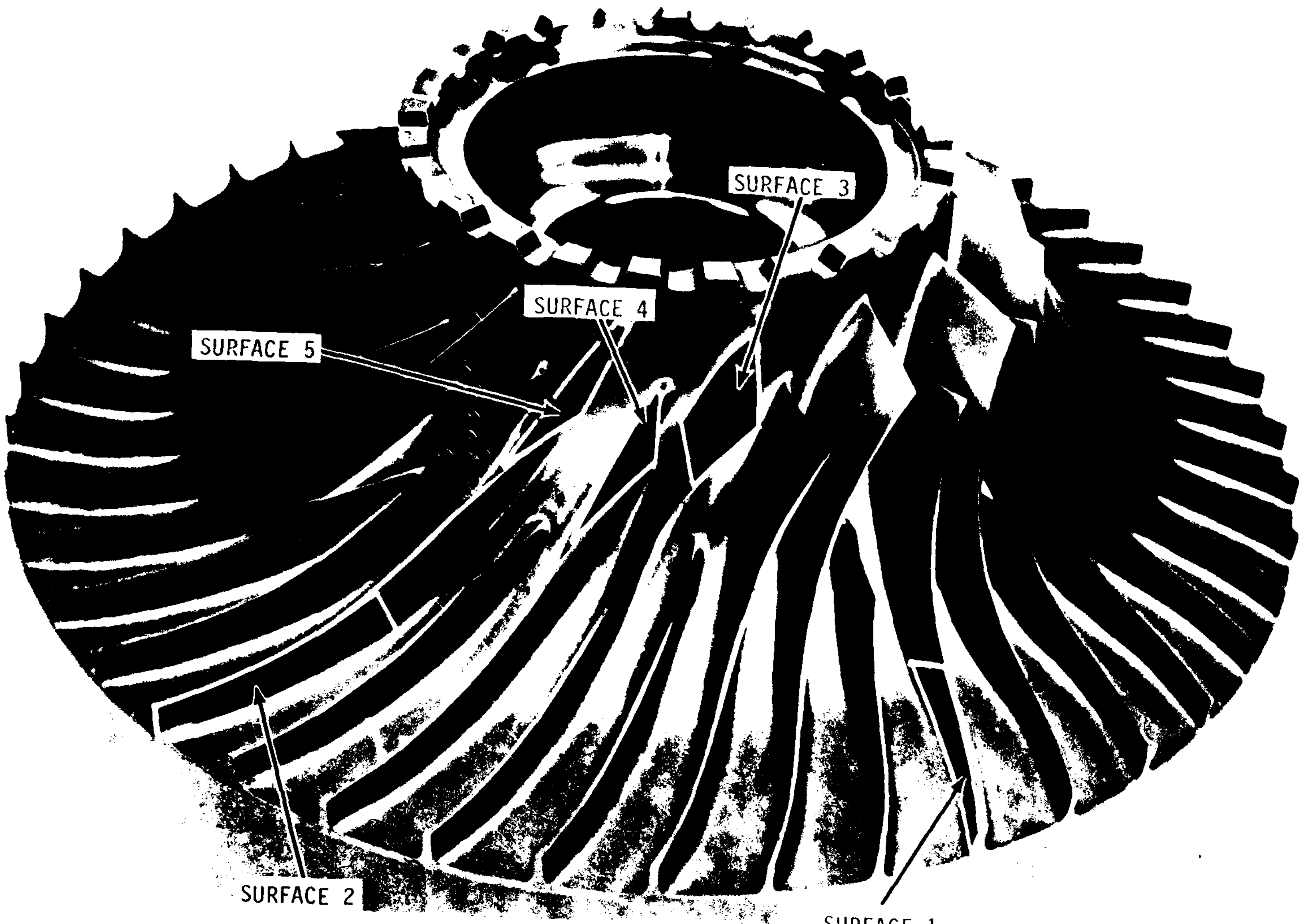



Figure 35. View Showing Five Surfaces Covered by GEMESH Program.

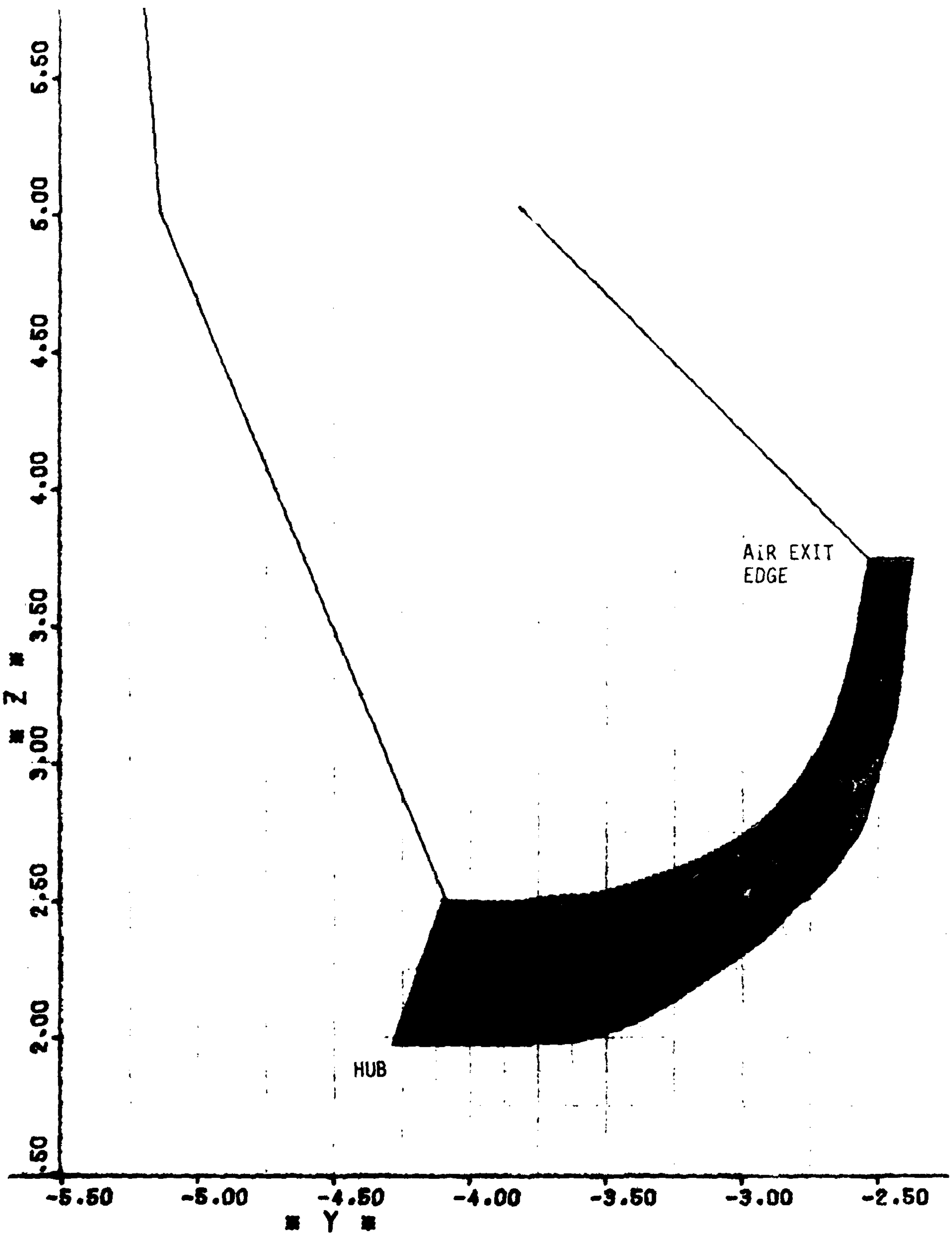



Figure 36. Computer Plot of Toolpaths to Finish an Airfoil Surface of a Simulated Impeller.

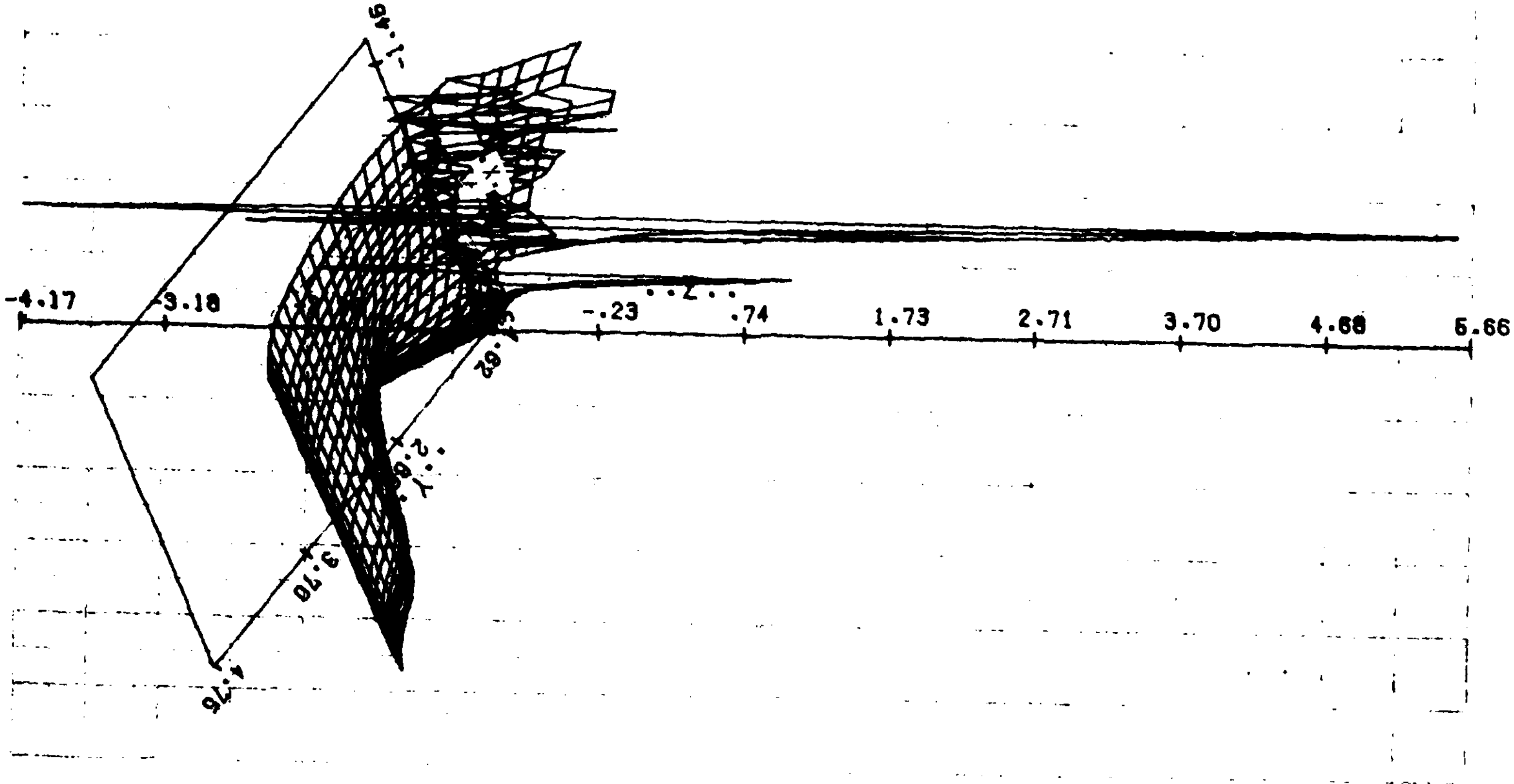



Figure 37. Computer Plot of GEMESH Surface Generated Through Engineering Data.

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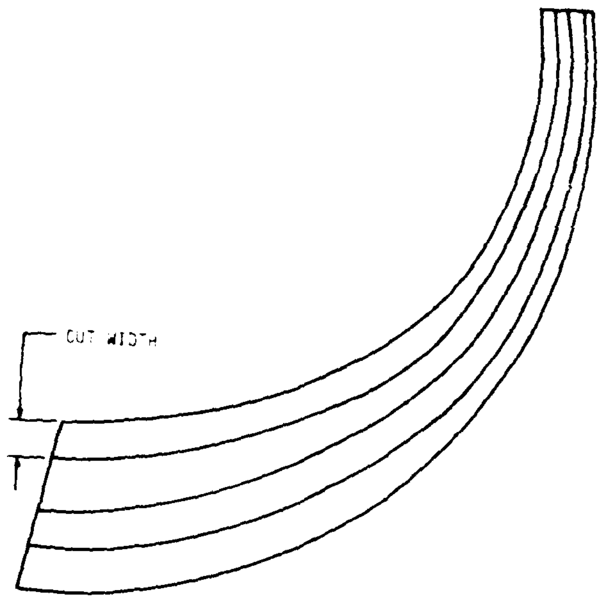


Figure 38. HECTRAN Cutter Paths.

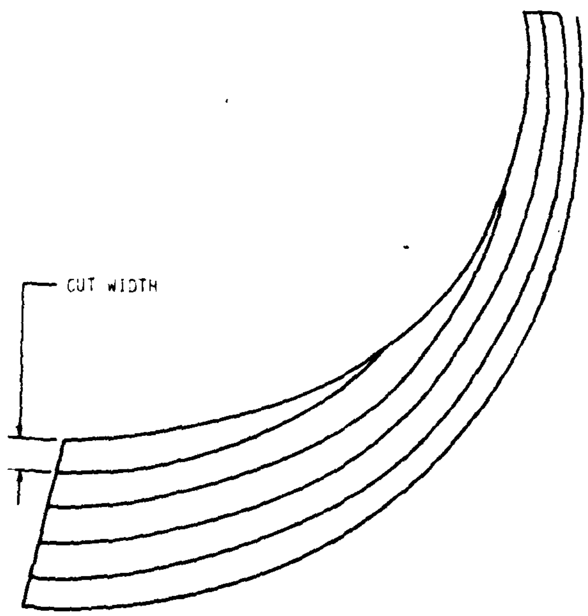


Figure 39. Modified HECTRAN Cutter Paths.

CONTOUR MILLING
OF
BLISKS

# CONTOUR MILLING OF BLISKS

## INTRODUCTION

Two different types of machining operations are required to produce blisk airfoils from solid forged material. The first is rough machining to generate a rough airfoil shape by removing a relatively large volume of material. The second is finish machining to produce precise geometry and surface texture which can be transformed into finished airfoils by a finishing process. The development program plan included provision for the evaluation of alternative processes for rough machining. The plan specified that finish machining would be done by multiple axis NC contour milling.

Several processes were considered for rough machining. These were broaching, electrical discharge machining, electrochemical machining, and contour milling. Contour milling offered the greatest promise. It was concluded that it could produce airfoil geometry that was so nearly like required final geometry, that semi-finish machining would not be required prior to finish machining; therefore total machining cost could easily be less with contour milling. The probability of encountering development problems that could delay the program schedule and the transition to volume production, was judged to be smaller with contour milling. Furthermore, rough contour milling could be done on the same machine as finish contour milling, which would avoid the need for different tool, equipment, and process development, and which would simplify manufacturing operations under volume production conditions. Therefore, rough contour milling was selected as the rough machining process.

Blisk contour milling development was begun before the 5-axis milling machine was available, so that airfoil NC milling trials could begin with this machine as soon as it was ready for use. Tests were devised that produced the information needed to select cutting methods, cutting paths, cutting fluid, cutter material and geometry, and cutting parameters, so that NC programs could be developed, part holding fixtures could be designed and made, and cutters could be procured. Conventional and NC production machines were used in these tests, as well as laboratory equipment and instruments. Small bar material was used for initial tests, since material of a larger size was not avilable.

After the 5-axis development milling machine became available, the final steps in contour milling development were completed. Material of a size that allowed simulating complete blisks was used. Most tests were made with 17-4PH alloy which has machining characteristics like the AM355 alloy of which actual blisks are made. Final tests were made with AM355.

## ROUGH CONTOUR MILLING

### Initial Investigation

Tests were made to determine the feasibility of end milling airfoils with the relatively thin leading and trailing edges required for blisks, and to determine if reasonabl cutter life appeared to be attainable with practical cutting parameters. First tests were made using a 2-axis tracer milling machine to produce simulated airfoils about the size of Stage 2 blisk airfoils. The simulated airfoils did not have any twist, since a 4-axis machine is needed for this. The test arrangement is illustrated in Figure 40 (pg 101). A simulated

ROUGH CONTOUR MILLING - Continued

airfoil is shown in Figure 41 (pg 101). The piece from which it was made was of the same alloy and heat treatment as for blisks. It is shown in Figure 42 (pg 102). The cutter is described in Table 4; cutter material was chosen to allow high speeds and feed rates with reasonable life. A down feed (cut width) of 0.060 inch was used with lineal feed rates (the velocity of the axis of the cutter with respect to the cut surface) up to 8 inches per minute (in/min). IPM cutting speed (surface speed) was 115 surface feet per minute (sft/min). Sulphochlorinated oil was used as cutting fluid to minimize abrasive wear. Results of these tests were satisfactory.

TABLE 4
ROUGH CONTOUR MILLING CUTTER
USED IN INITIAL INVESTIGATION

| | | |
|---|---|---|
| Material | - | General Electric Carbide Grade 883 |
| Size | - | 5/16 inch diameter |
| Extended Length | - | 2 inches |
| Flute Length | - | 1 inch |
| Helix Angle | - | 18 degrees |
| Style | - | Right hand spiral, right hand cut |
| No. Flutes | - | 6 |
| Corner Angle | - | 1/16 inch |

Further tests were made using the tracer mill and conditions like those described above. However, the test pieces from which simulated airfoils were milled were cast in low melting temperature alloy to evaluate the influence of using a matrix to support airfoils. The test piece is shown in Figure 43 (pg 103). This was done in case it should be found later on that blisks should be preslotted to remove most of the material between airfoils before rough contour milling, requiring that the remaining sections be supported by a matrix to limit deflection [illegible] rough contour milling airfoils from the. The matrix had no significant [illegible] wear as shown in Figure 44 (pg 104). Furthermore, it did not affect the [illegible] and removal of chips.

[illegible] tests were made with the tracer mill under similar conditions to [illegible] described to determine the influence on cutter wear of cutting [illegible] larger piece of material, to simulate rough contour milling [illegible] forging without preslotting. It was concluded that it would [illegible] airfoils from solid forgings without preslotting. Although [illegible] to progress more rapidly, this wear would be offset by the [illegible] would be needed for preslotting. Although lower lineal feed [illegible] when milling solid forgings, the greater time this would [illegible] the time required for a preslotting operation.

ROUGH CONTOUR MILLING - Continued

Investigation of Cutter Wear Relative to Milling Parameters

A more extensive investigation of cutter wear was made to determine the influence of cutting parameters on wear. This was done with a 3-axis NC milling machine. With this machine it was possible to readily use a wider range of cutting parameters than could be obtained with the tracer mill. Furthermore, parameters could be obtained easily and controlled accurately and the machine had a spindle with stiffness characteristics closer to the 5-axis development milling machine then being designed and built. Only water base cutting fluid could be used with this machine, however, it was judged that this would not have a major effect on test results.

Cutters were used like those in previous tests. Airfoils were milled from matrial like that shown in Figure 42 (pg 102) with metallurgy like blisk forgins. Cutting speed ranged from 115 (sft/min) to 165 (sft/min). Feed rates ranged from 3 to 12 in/min. Down-feeds ranged from 60 mils to 240 mils. Examples of simulated airfoils produced in these test are shown in Figure 45 (pg 105).

Test results are given in Table 5 (pg 76). An analysis of results is shown in Figure 46 (pg 106) which suggested the following hypothethis.

Tangential force at the cutting edge of each flute, per unit of flute length engaged in cutting, increases sharply as cut thickness (chip load) is increased by increasing feed rate, when other parameters are held constant. As this force increases cutting edge wear tends to increase. At some point, the cutting edge may fracture (chip) and vibration may develop; eventually a force per unit length will be reached which will cause flute fracture.

Total tangential force at the cutting edge of each flute will increase proportionally with increasing cut length, by increasing downfeed, while other parameters are held constant. That part of the engaged cutting edge immediately adjacent to the section of the flute which is not cutting, will be given support by the unloaded noncutting section above it, and will be able to withstand greater force per unit length without fracture. As cut length is increased, the support given to that part of the cutting edge at the end of the flute will decrease. At some combination of cut thickness and length, the end of the flute will fracture.

Furthermore, as total tangential force increases, the likelihood of vibration will increase; this will induce cutting edge fracture (chipping) and will lead to further increases in force and ultimately to flute fracture.

Alternatively, if the forces on the cutting edges are not great enough to cause flute fracture, increasing total force will eventually cause fracture through the shank of the cutter. Conditions during the tests were obviously appropriate to produce flute fracture, rather than fracture through the cutter shank.

No clear effects are shown in the chart of Figure 46 (pg 106) from changes in cuttring speed. It is probable that the only significant effect was a reduction of cut thickness, which is provided for in the design of the chart.

ROUGH CONTOUR MILLING - Continued

TABLE 5
TEST RESULTS
NC MILLING OF SIMULATED AIRFOILS
ON 3-AXIS NC MACHINE

| Test No | Quantity of Airfoils Cut | Cutter Condition | Remarks |
|---|---|---|---|
| 1 | 1 | .006 inch wearland; no edges chipped. | Good cutting action; slow rate. |
| 2 | 1 | .006-.008 inch wearland; light edge chipping with wearland. | Light audible vibration; slightly uneven wear. |
| 3 | 1 | .004-.006 inch wearland; light edge chipping on 2 of 6 flutes. | Good cutting action |
| 4 | - | Cutter broke on 3rd pass. | Light wear except 1 flute fractured followed by shank fracture. |
| 5 | - | Cutter broke on 1st pass. | All flutes fractured; shank did not break. |
| 6 | 1 | .006-.010 inch edge chipping; no normal wear. | Light audible vibration. |
| 7a | 1 | .004-.006 wearland except 1 edge chipped to .010 inch | Good cutting action; chosen for life test. |
| 7b | 2 | Cutter broke on 2nd airfoil with 17 of 20 passes complete. | Failure was sudden; all flutes fractured; shank did not break. |
| 7c | 2-1/2 | Cutter broke on 3rd airfoil with 11 of 20 passes complete. | Sudden failure; all flutes fractured; shank did not break. |
| 8 | 1 | .004-.006 inch wearland, chipping to .010 inch on 4 of 6 flutes. | Moderate audible vibration. |
| 9 | 4 | .003-.004 inch wear; negligible chipping. | Cutter in excellent condition; good cutting action, chosen for life test. |

ROUGH CONTOUR MILLING - Continued

Changes in cutting conditions, such as the use of suphochlorinated oil as cutting fluid, or changing cut depth by using different test block dimensions, would be expected to alter the parameters at which the different conditions shown in Figure 46 (pg 106) would appear. However, it is probable that the overall pattern would be unchanged.

Cut thickness was calculated from:

$$CT = \frac{V}{NK} \qquad \text{(Eq 1)}$$

where CT = cut thickness (inches).

V = lineal feed rate (in/min).

N = cutting speed (rpm).

K = number of cutting edges or flutes.

Information on the derivation of this equation is given in Reference 1.

Results of the tests provided a logical basis for selecting cutting parameters in relation to metal removal rate and cutter wear rate. They also provided numerical values of parameters to be used in subsequent investigations.

Preliminary 4-Axis Contour Milling

Tests to investigate 4-axis milling of actual blisk airfoils were conducted using a production machine. While this machine had characteristics which were very different from the 5-axis development machine then being built, it made possible the milling of Stage 1 blisk airfoils with NC programs and cutting conditions reasonably similar to those being considered for use with the development machine. The airfoil tracing machine being built for measurement of airfoil geometry was not yet available, consequently, a very different method had to be used to measure the airfoils produced in these tests.

A fixture was designed and produced for holding and locating a test block for contour milling by tilting the block at the average helix angle of a blisk airfoil. It is shown in Figure 47 (pg 107). The fixture has three holding positions, spaced to coincide with the stacking axes of three consecutive Stage 1 blisk airfoils. The center position is the machining position and was used first to machine two aluminum blocks to airfoil geometry. These airfoils were then fastened into the left and right holding positions to act as adjacent airfoils while an AM355 block was machined in the center position. This arrangement allowed cutter clearances to be checked during machining of the AM355.

The test blocks prepared for this investigation simulated a preslotted blisk and provided sufficient material for secure clamping and for machining the twisted contour.

---

1. Shaw, Milton; METAL CUTTING PRINCIPLES, MIT Press.

ROUGH CONTOUR MILLING - Continued

The tool data and test parameters are given in Table 6.

TABLE 6
CONDITIONS FOR PRELIMINARY 4-AXIS MILLING OF STAGE 1 BLISK AIRFOILS

| | | |
|---|---|---|
| Tool Grade | - | 883 Carboloy |
| Tool Geometry | - | 6-Flute End Mill |
| Tool Size | - | 5/16 inch dia 0.060 inch rad |
| Cutting Speed | - | 120 sft/min |
| Lineal Feed | - | 3 and 6-in/min |
| Downfeed | - | 0.060 and 0.120 inch |
| Cutting Fluid | - | Sulphochlorinated Oil |

Figure 48 (pg 108) shows the milled AM355 airfoil (center) and the adjacent aluminum airfoils, produced under NC control of the 4-axis NC milling machine. The rough texture and broken leading and trailing edges on the machined aluminum were caused by the low rigidity of the aluminum airfoils, as well as the inability to machine at the high cutting speeds required by aluminum. The AM355 airfoil was produced without any contact between the cutter and the aluminum airfoils. A sinble cutter machined a total of four AM355 airfoils with a wearland of 0.004-0.006 inch and with minor chipping.

The geometry of the simulated blisk airfoils was measured by reflective projection, after cutting the airfoils at seven of the eleven sections shown on the part drawings and comparing them with the nominal sections appearing in the drawings. The contours were projected at 10X magnification. Sections examined are B through J as shown in Figure 49 (pg 109).

The projection measurements showed a close correlation with design contours. The differences between actual and programmed geometry were relatively small. The sources of differences include cutter deflection, the precision of the machine used, the precision of the part h olding fixture, and the measurement techniques used on the airfoils.

Rough Contour Milling Plan

Tests described in the Investigation of Cutter Wear Relative to Milling Parameters section (pgs 75-77) indicated that it was not necessary to preslot blisk forgings to remove the majority of the material between airfoils before rough contour milling the airfoils. These tests indicated that there would be no economic advantage for the additional preslotting operation. This was confirmed by additional tests on a conventional vertical spindle milling machine, in which cuts were made on AM355 bar stock. Consequently, rough contour milling of solid forgings was selected.

ROUGH CONTOUR MILLING - Continued

Two alternatives for milling airfoils were evaluated. One consisted of milling airfoils by moving the cutter in a series of paths that followed th airfoil contour as shown in Figure 43 (pg 103). The first path would machine the upper part of the airfoil, for example, the part above Section J in Figure 49 (pg 109). The next path would machine that part of the airfoil immediately below the first part machined, for example, the part between Sections G and J. Successive paths would be used to produce the complete airfoil down to just above the platform surface between Sections A and B. This plan would produce complete airfoils, one at a time.

After rough contour milling, the airfoils would be finished contour milled in the same way. However, as described in the Finish Contour Milling section (pgs 82-100), some means would be needed to support the airfoils while they were finished so that they would not deflect as the result of cutting forces, since deflection would affect the finished dimensions of the airfoils.

The second alternative consisted of moving the cutter in a series of paths to remove material between two adjacent airfoils, to produce a pocket. The cutter would follow paths like that shown in Figure 50 (pg 110). The first path would remove material at the upper part of the airfoil, as in the first alternative. Successive cutting paths would remove material in the same way. After the pocket was rough contour milled, it would then be finish contour milled, with the cutter following a series of similar cutting paths. Airfoil deflection would not occur since only the facing sides of each of two adjacent airfoils would be finished and these would be milled from solid material. After rough and finish contour milling every other pocket, these pockets would be filled with a matrix alloy and the remaining pockets would be milled with the matrix supporting the airfoils to essentially prevent deflection.

The second alternative was chosen as the most feasible. To minimize cutter vibration and thereby reduce the rate of cutter chipping wear, cutting paths were designed to produce stepped cuts. This was done by feeding the cutter down a fixed distance, for example 60 mils, prior to the time it enters the solid material to start cutting. Downfeed would therefore occur as the cutter moved along each of the two parts of the cutting path shown as horizontal lines in Figure 49 (pg 109). As a result, the cutter is engaged in cutting over a full 180-degree arc around the cutter throughout the entire cutting path, except when it enters a cut or when it is totally unengaged as it moves from one cut to the next along the horizontal lines in Figure 49. Engagement over an arc of 180-degrees limits movement of the cutter perpendicular to the direction of lineal feed, and therefore minimizes vibration in this perpendicular direction. As a consequence, chipping wear is minimized.

The milling plan that was devised provided for programming to leave approximately 20 mils of material on airfoil and platform surfaces to be removed by finish contour milling. This allows for variations in rough contour milled geometry as the result of variations in cutter deflection caused by varying cutting forces, which wer expected to sometimes cause removal of more material than called for by the NC program.

ROUGH CONTOUR MILLING - Continued

The amount left for removal during finish contour milling was expected to exceed the programmed amount, also as a result of cutter deflection, and as a result of the surface waves produced by successive cutting paths.

Surface waves are shown in Figure 51 (pg 111). The peak valley distance (waviness distance D) for the surface waves depends upon the angle of the cutter axis to the designed airfoil surface ($\alpha$), upon the corner radius of the cutter (R) and upon the magnitude of the downfeed between cutter paths (X). This is illustrated in Figure 52 (pg 112), which was produced by computer graphics. The illustration shows that with an angle of 4 degrees, a cutter with a corner radius of 60 mils and a downfeed of 200 mils, that the peak to valley distance is about 5 mils.

Cutters

The diameter and length of cutters was established by analyzing the geometry of the pockets between airfoils of all blisks. It was essential that cutter diameter be as great as possible and length as short as possible to allow maximum cutting force. Conventional end mill geometry was chosen, with relatively short flutes to provide maximum shank strength where bending forces can produce greatest stress. Solid carbide was chosen for high strength to allow high cutting forces that are needed for maximum metal removal rates, and to withstand the high temperatures that maximum metal removal rates produce, without excessive cutter wear rates. Grade 883 Carboloy* was chosen because it offers a good combination of abrasive wear resistance and chipping wear resistance.

Typical cutter requirements are shown in Figure 53 (pg 113), and a typical cutter is shown in Figure 54 (pg 114).

Cutting Forces

Tests were made to determine the relationships between cutting parameters and cutting forces. This information was needed so that parameters could be selected which would produce maximum metal removal rates, without producing forces that would result in a high risk of cutter breakage. Cutters used in the tests were the same as those selected for rough contour milling. Material in which test cuts were made was AM355 alloy which conformed to blisk design requirements. A conventional milling machine was used in the tests, and it was equipped with a laboratory dynamometer.

The test arrangement is shown in Figure 55 (pg 115). Stepping cuts were used as shown in this illustration. The test results were used to construct nomograms shown in Figures 56-57 (pgs 116-117), which give maximum resultant bending forces on cutters over a range of parameters.

Sulphochlorinated oil and water base cutting fluids were tested, and lower forces were found with the oil, which was chosen for use in actual blisk milling. The water base fluid was 20 to 1 Trimsol.

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ROUGH CONTOUR MILLING - Continued

Dynamic recordings of cutting forces, not shown, indicated some variations in forces while cutting; maximum forces were used to construct these illustrations. Breaking forces, obtained during cutting tests, were slightly smaller than breaking forces from static transverse rupture tests; breaking forces from cutting tests were used for the illustrations. Axial forces were relatively small in relation to cutter bending forces, and were not used for the illustrations. Bending forces, along the direction of feed, were substantially greater than forces normal to the feed direction, and were only slightly smaller than the resultant of both forces; resultant forces were used for the illustrations.

The illustrations show estimates for cutting speeds which are near the maximums that gave reasonable cutter life during previous development work. These estimates were calculated from cutting test results, and should be reliable since surface speed was considered to have negligible effect on force. Calculations were based on chip loads and corresponding forces obtained during tests, but at greater surface speed and proportionally increased feed rate.

The forces shown in the illustrations are for new cutters. Forces tend to increase as cutters wear. The results of tests made with a worn cutter showed forces that were nearly double those encountered with a new cutter.

The results show that, for any selected resultant bending force, greater metal removal rates are possible with smaller downfeeds than with larger downfeeds. However, a cutter used with smaller downfeed may wear as much while removing less material, as a cutter used with greater downfeed. Therefore, increased metal removal rate can only be attained by making more cutter changes, and with more cutter grinding expense.

The illustrations are designed to allow choosing feed rates that will produce a selected force with a predetermined surface speed, and any desired downfeed. The selected force for a new cutter should be a fraction of the breakingg force, such as 1/3 to 1/2 of the breaking force, to allow for increased force as the cutter wears. The maximum force for a worn cutter should probably not exceed 2/3 to 3/4 of the average breaking force.

An example of how feed rate may be chosen to limit force to a selected value is shown in Figure 56 (pg 116) for a 3/16 inch diameter cutter milling AM355. The force limit for a new cutter is selected as 60 pounds; with a speed of 180 sft/min obtained at 3600 rpm and a downfeed of 60 mils; the metal removal rate will be 0.085 in/min with a feed rate of 8 in/min and a chip load of 0.56 mils. Alternatively, with the same 60 pound force limit, and 30 mil downfeed, the metal removal rate will be 0.17 in/min, at a feed rate of 30 in/min and a chip load of 2.1 mils. Cutter wear can be allowed to progress in each case to give a force of over 100 pounds, giving a reasonable margin to the average breaking force of 150 pounds. The force limit selected for a new cutter will depend upon allowed cutter wear; it can be greater if less wear is allowed.

ROUGH CONTOUR MILLING - Continued

Optimum downfeed and feed rate for production milling, and allowable cutter wear, must be established by actual milling of production parts. The illustrations can be used to select logical downfeeds and feed rates for trials. By observing cutter wear, and recording cutter breakage, feed rate selections can be progressively made from the illustrations to obtain optimum downfeed, feed rate, allowable cutter wear, and cutter life, considering both machining time and cutter regrind expense.

### Fixtures

Fixtures needed to hold blisks on the rotary tables of the 5-axis milling machine were designed and built before the development machine was available for use. A typical fixture holding a Stage 1 blisk is shown in Figure 58 (pg 118). The same fixtures were used for rough and finish contour milling.

### Rough Contour Milling with the Development Machine

As soon as the development machine became available, airfoils were rough and finish contour milled, using previously developed NC programs. Results were analyzed, with the help of measurements of airfoil geometry. Rough contour milling parameters were selected for initial use that gave good cutter life. NC program changes were made to adjust rough milled geometry as needed to produce finish milled airfoils that conformed as closely as possible to design requirements.

## FINISH CONTOUR MILLING

### Initial Investigation

A simple laboratory dynamometer designed specifically for measurement of low cutting forces was used to investigate average tangential force with cutting conditions that were under consideration for blisk and impeller finish contour milling. The test arrangement is shown in Figure 59 (pg 119). Cutters used were made of tungsten carbide; they included a 1/8-inch diameter ball burr with 19 teeth, a 3/8-inch diameter ball burr with 32 teeth, and a 5/16-inch diameter straight shank burr with 20 teeth. Cuts were made on the sides of test pieces made of AM355 alloy, the same as used for blisks. Sulphochlorinated oil was used as cutting fluid. Ball cutters and cut geometry are shown in Figures 60-61 (pg 120-121). Typical results of tests are shown in Table 7 (pg 83).

TABLE 7
TEST DATA SUMMARY OF TANGENTIAL CUTTING FORCE FOR BLISK FINISH CONTOUR MILLING OBTAINED WITH DYNAMOMETER

| Test No. | Tangential Force (lb) | Cutter (rpm) | Cutter (sft/min) | No. Of Cutter Teeth | Lineal Feed Rate (in/min) | Depth Of Cut (mils) | Down-feed (mils) | Area Of Cut (Square mils) |
|---|---|---|---|---|---|---|---|---|
| CUTTING TOOL - 3/18-INCH-DIAMETER BALL BURR | | | | | | | | |
| 1 | 2.9 | 1,900 | 185 | 32 | 16.0 | 30 | 10 | 300 |
| 2 | 4.5 | 1,900 | 185 | 32 | 16.0 | 40 | 10 | 400 |
| 3 | 6.6 | 1,900 | 185 | 32 | 16.0 | 50 | 10 | 500 |
| 4 | 2.0 | 3,750 | 365 | 32 | 16.0 | 30 | 10 | 300 |
| 5 | 1.7 | 4,750 | 463 | 32 | 16.0 | 30 | 10 | 300 |
| 6 | 2.0 | 4,750 | 463 | 32 | 16.0 | 20 | 24 | 480 |
| 7 | 2.0 | 4,750 | 463 | 32 | 36.0 | 20 | 12 | 240 |
| 8 | 2.0 | 6,000 | 585 | 32 | 7.5 | 20 | 60 | 1,200 |
| CUTTING TOOL - 5/16-INCH-DIAMETER STRAIGHT SHANK BURR WITH .060-INCH END RADIUS | | | | | | | | |
| 9 | 4.0 | 6,000 | 585 | 20 | 8.3 | 60 | 15 | 900 |
| 10 | 4.0 | 6,000 | 585 | 20 | 19.2 | 60 | 10 | 600 |
| 11 | 4.0 | 6,000 | 585 | 20 | 39.4 | 60 | 7 | 420 |

Y axis locked for all tests to maintain depth of cut.

Test results were analyzed for the purpose of estimating the minimum chip thickness that could be cut, by relating cutting energy to calculated chip thickness. This relationship is shown in Figure 62 (pg 122); it indicates that minimum chip thickness probably falls between 100 and 200 microinches. This information was needed for use in the selection of cutting parameters.

FINISH CONTOUR MILLING - Continued

Test results indicated that tangential cutting force would be relatively low, and therefore, cutter deflection due to tangential force would not be significant. They also showed that surface roughness with a stiff cutting system could be less than 100 microinches average amplitude (AA), since actual roughness of cut surfaces under some conditions did not exceed about 140 microinches AA with the low stiffness introduced into the test system by the dynamometer.

Test results also indicated that cutter wear would not progress at an excessive rate. Wear data are shown in Figure 63 (pg 123); chatter developed after 0.6 cubic inches of metal was removed by a 3/8-inch diameter ball burr. This volume was equivalent to that which will be required to finish several airfoils.

Investigation of Normal Cutting Force

Cutting force normal to the surface of airfoils is of primary importance in blisk airfoil finish contour milling. This force will cause the cutter to deflect away from the airfoil surface, so that thickness of the airfoil will be greater by the amount of the deflection. This force can cause the airfoil to deflect away from the cutter with the same result. The sum of cutter and airfoil deflection will vary as the result of changes in cutting conditions which affect normal force, while the cutter passes over the airfoil surface, and as the result of changes in airfoil deflection characteristics due to differences in airfoil stiffness at various locations on the airfoil.

A conventional milling machine was used for investigating normal force. An experimental method was devised to obtain cutter deflection over a range of depths of cut, and with other cutting conditions applicable to blisk airfoil finish contour milling. The experimental method is illustrated in Figure 64 (pg 124). Cutter deflection was determined by measuring deviation of the cut surface from the plane coincident with the axis of the cutter. This was done with acceptable accuracy with a ContouReader, as shown in Figure 65 (pg 125). Normal force was obtained by translating cutter deflection into force, through application of the deflection characteristics for the cutter and machine spindle combination, which was established by separate force and deflection measurements. Typical test results are shown in Tables 8-9 (pgs 85-86).

A stepwise multiple linear regression computer program was used to obtain from the test results equations which would give for a particular cutter geometry approximate normal cutting force as a function of cutting speed, downfeed (width of cut), depth of cut, lineal feed rate (feed rate of the cutter axis with respect to the cut surface), and the number of teeth on the cutter. The equations were used to predict approximate normal cutting force for cutting conditions that could be used for finish contour milling. For example, they indicated that with a sharp ball end cutter having 30 teeth, normal force would be in the order of 10 pounds, with a lineal feed rate of 30 in/min, cutter speed of 3000 (rpm), a depth of cut of 30 mils, and a downfeed of 10 mils.

FINISH CONTOUR MILLING - Continued

TABLE 8
UPCUTTING TESTS TO DETERMINE NORMAL CUTTING FORCES

| Test Parameters | | | | | Test Results | | |
|---|---|---|---|---|---|---|---|
| No. of Cutter Teeth | Cutter Speed (rpm) | Depth of Cut (in) | Feed Rate (in/min) | Down Feed (in) | Calculated Force (lb) | Measured Surface Roughness Average Amplitude ($\mu$/in) | Calculated Chip Thickness (mils) |
| 20 | 2,000 | .005 | 10 | .010 | 5.78 | 65 | 31 |
| 20 | 2,000 | .005 | 10 | .010 | 4.75 | 55 | 31 |
| 20 | 2,000 | .005 | 30 | .010 | 6.66 | 90 | 93 |
| 20 | 2,000 | .005 | 30 | .010 | 5.71 | 50 | 93 |
| 20 | 2,000 | .030 | 10 | .010 | 10.74 | 65 | 57 |
| 20 | 2,000 | .030 | 10 | .010 | 10.95 | 55 | 57 |
| 20 | 2,000 | .030 | 30 | .010 | 12.8 | 90 | 171 |
| 20 | 2,000 | .030 | 30 | .010 | 14.76 | 50 | 171 |
| 20 | 10,000 | .005 | 10 | .010 | 2.5 | 55 | 6 |
| 20 | 10,000 | .005 | 30 | .010 | 6.6 | 65 | 19 |
| 20 | 10,000 | .030 | 10 | .010 | 5.0 | 100 | 11 |
| 20 | 10,000 | .030 | 30 | .010 | 15.4 | 60 | 34 |
| 30 | 10,000 | .005 | 10 | .010 | 0.83 | 75 | 4 |
| 30 | 10,000 | .005 | 30 | .010 | 0.83 | 65 | 12 |
| 30 | 10,000 | .005 | 30 | .030 | 4.95 | 100 | 21 |
| 30 | 10,000 | .030 | 10 | .010 | 2.08 | 75 | 7 |
| 30 | 10,000 | .030 | 30 | .010 | 4.16 | 70 | 23 |
| 30 | 10,000 | .030 | 30 | .030 | 14.46 | 100 | 37 |
| 30 | 10,000 | .040 | 10 | .010 | 3.33 | 60 | 8 |

Constant Conditions:

Bridgeport Miller - 10,000 rpm obtained with Hispeed attachment.
3/8-inch diameter ball burrs - carbide burr - steel shank - sharp cutter.
Sulphochlorinated oil
AM355 Material

FINISH CONTOUR MILLING - Continued

TABLE 9

DOWNCUTTING TESTS TO DETERMINE NORMAL CUTTING FORCES

| Test Parameters | | | | | Test Results | | |
|---|---|---|---|---|---|---|---|
| No.of Cutter Teeth | Cutter Speed (rpm) | Depth of Cut (in) | Feed Rate (in/min) | Down Feed (in) | Calculated Force (lb) | Measured Surface Roughness Average Amplitude ($\mu$/in) | Calculated Chip Thickness (mils) |
| 20 | 2,000 | .005 | 30 | .010 | 4.76 | 40 | 93 |
| 20 | 2,000 | .005 | 30 | .010 | 8.67 | 60 | 93 |
| 20 | 2,000 | .030 | 30 | .010 | 10.0 | 40 | 171 |
| 20 | 2,000 | .030 | 30 | .010 | 13.22 | 60 | 171 |
| 20 | 10,000 | .005 | 10 | .010 | 3.33 | 50 | 6 |
| 20 | 10,000 | .005 | 30 | .010 | 5.4 | 85 | 19 |
| 20 | 10,000 | .005 | 32.5 | .010 | 4.13 | 60 | 20 |
| 20 | 10,000 | .030 | 10 | .010 | 7.5 | 50 | 11 |
| 20 | 10,000 | .030 | 30 | .010 | 14.1 | 100 | 42 |
| 20 | 10,000 | .030 | 32.5 | .010 | 7.85 | 60 | 37 |
| 30 | 10,000 | .005 | 10 | .010 | 0.83 | 60 | 4 |
| 30 | 10,000 | .005 | 30 | .010 | 2.5 | 70 | 12 |
| 30 | 10,000 | .005 | 30 | .020 | 4.54 | 95 | 17 |
| 30 | 10,000 | .005 | 30 | .040 | 8.26 | 125 | 23 |
| 30 | 10,000 | .015 | 30 | .010 | 4.16 | 70 | 18 |
| 30 | 10,000 | .030 | 10 | .010 | 2.08 | 65 | 8 |
| 30 | 10,000 | .030 | 30 | .010 | 6.66 | 70 | 23 |
| 30 | 10,000 | .030 | 30 | .020 | 14.04 | 95 | 32 |
| 30 | 10,000 | .030 | 30 | .040 | 19.83 | 125 | 43 |

Constant Conditions:

Bridgeport Miller - 10,000 rpm obtained with Hispeed attachment.
3/8-inch diameter ball burrs - carbide burr - steel shank - sharp cutter.
Sulphochlorinated Oil
AM355 Material

FINISH CONTOUR MILLING - Continued

A typical equation obtained through this investigation which is for the cutter described above, is:

$$FORCE = 10.73 + 325.07DF + 217.58DOC + .1614IPM - .2028KRPM - .58\ TETH \qquad (Eq\ 2)$$

where TETH = number of teeth in cutter

DOC = depth of cut in inches

DF = downfeed in inches

IPM = feed rate in inches per minute

KRPM = cutter speed in $\frac{RPM}{1000}$

FORCE = normal force in pounds

Cutters

The diameter and associated length of the cutters needed for finish contour milling blisks was established by analyzing the geometry of the pockets (spaces) between airfoils of all blisks. A typical analysis is shown in Figure 66 (pg 126).

Ball end cutters having close tolerances were required for milling; feasible tolerances were investigated with cutter manufacturers. Solid carbide cutters were selected to minimize deflection, so deflection variability would be small in relation to airfoil contour design tolerances of $\pm$1.5 mils and thickness tolerances of +4 to -3 mils from nominal. Grade 883 Carboloy* was selected to obtain a reasonable compromise between hardness upon which abrasive wear depends and toughness upon which chipping wear depends; both wear modes were expected to be important determinants of useful cutter life.

Sample cutters were procured and their geometry was measured to determine conformance with requirements. It was concluded that the ball end of cutters used for airfoil milling should be truncated to allow cutter manufacturers to hold that end in a centering device, as well as the shank end, to better control dimensions.

Typical cutter requirements are shown in Figures 67-68 (pgs 127-128). Typical cutters are shown in Figures 69-70 (pgs 129-130).

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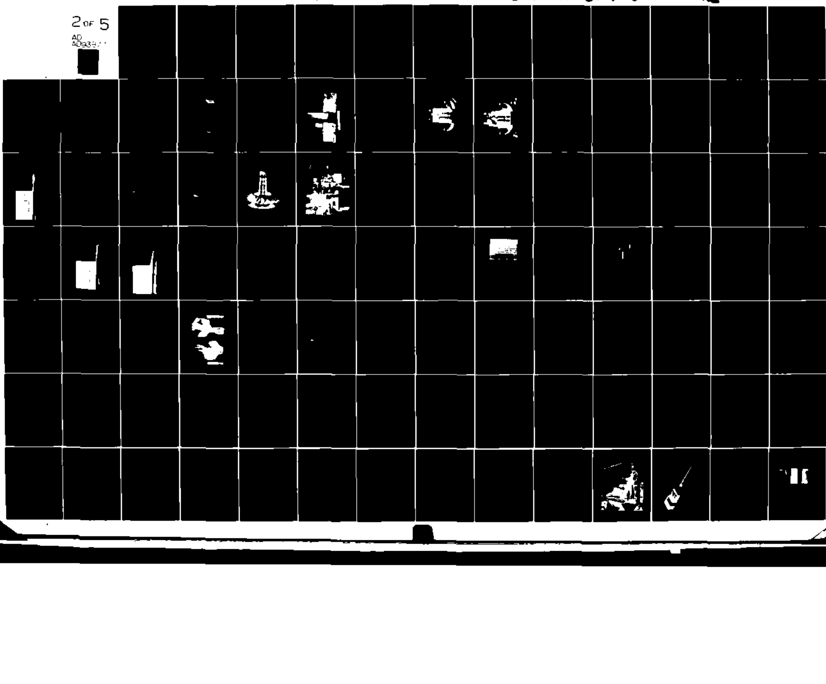


FINISH CONTOUR MILLING - Continued

## Cutter Deflection Characteristics

The deflection characteristics of cutters were determined by calculation with cantilever beam equations for the geometry selected for each type cutter. FORTRAN programs were written so calculations could be made with a computer for all cutter types, diameters, and extended length. A typical program and typical output from the program are shown in Table 10 (pg 89).

This table shows that with a 0.1875 inch-diameter cutter extended 1 inch from the cutter holder, deflection would be about 0.6 mils with a normal force of 10 pounds. These were the most favorable conditions anticipated for milling Stage 5 blisk airfoils. Higher normal force which was expected with cutter wear, would produce proportionally greater deflection. Therefore, cutter deflection was expected to be in the order of 1 mil.

Since deflection will occur in opposite directions on opposite sides of the airfoil, the total effect of cutter deflection on thickness was expected to be roughly 2 mils. Assuming that deflection while milling an airfoil could vary over a two to one range, airfoil thickness variability as a result of cutter deflection variability would be in the order of 1 mil. This was considered acceptable in relation to the design thickness limits of +4 to -3 mils.

## Investigation of Airfoil Deflection

Finished airfoil deflection was investigated initially since no practical means were available for producing rough contour milled airfoils having appropriate additional thickness. A scrap production Stage 1 blisk was used. Results showed relatively large deflection with normal force in the order of magnitude indicated by the previously described investigation. Therefore, an analytical approach was devised to investigate deflection of airfoils having appropriate rough contour milled thickness. This investigation included deflection with force applied at either the airfoil leading edge where thickness is smallest, or at the stacking axis where thickness is greatest. It included deflection with force applied along either the leading edge or the stacking axis at any distance from the airfoil tip.

First, a model was made to simulate the deflection characteristics of a finished airfoil on a scrap production Stage 1 blisk. Then a new model was made like the first but with thickness increased by 60 mils to simulate an airfoil which had been rough contour milled. The deflection characteristics of this model were then investigated under several conditions. These included application of normal force at different locations, and with thickness reduced to the thickness of the first model of a finished airfoil from the airfoil tip down to particular sections of the model. The test arrangement is shown in Figure 71 (pg 131).

## TABLE 10
## CUTTER DEFLECTION

```
PROGRAM IS FOR CARBOLOY 883 AT 94,000 000 MOD OF ELAS.
*#RUNH *=(CORE=5)
2 FORMAT (5X,F10.6,6X,3(F8.4,6X))
3 FORMAT (8X, HDELTX1,10X,5HFORCE,10X,2HEL,10X,4HDIAM)
WRITE (6,3)
FORCE=1.0
DIAM=0.0
EL=0.0
DO 30 I=1,6
DIAM=DIAM+.0625
EL=0.0
DO 35 J=1,6
EL=EL+0.25
YMOD=(0.05*DIAM**4.)
9 DELTX1=( FORCE*EL**3.)/(3*94000000.*YMOD)
WRITE (6,2) DELTX1,FORCE,EL,DIAM
35 CONTINUE
30 CONTINUE
99 STOP
END

ready
*RUNH
```

Deflection Values for Carboloy *883 Solid Shank Cutting Tools

DELTX1 = Deflection (Inches)
FORCE = Force on End of Tool (lb)
EL = Extended Length of Tool (Inches)
DIAM = Tool Shank Diameter (Inches)

*GE Trademark

12/15/75 14.815

| DELTX1 | FORCE | EL | DIAM | DELTX1 | FORCE | EL | DIAM |
|---|---|---|---|---|---|---|---|
| 0.000073 | 1.0000 | 0.2500 | 0.0625 | 0.000000 | 1.0000 | 0.2000 | 0.2500 |
| 0.000581 | 1.0000 | 0.5000 | 0.0625 | 0.000002 | 1.0000 | 0.5000 | 0.2500 |
| 0.001961 | 1.0000 | 0.7500 | 0.0625 | 0.000008 | 1.0000 | 0.7500 | 0.2500 |
| 0.004648 | 1.0000 | 1.0000 | 0.0625 | 0.000018 | 1.0000 | 1.0000 | 0.2500 |
| 0.009078 | 1.0000 | 1.2500 | 0.0625 | 0.000035 | 1.0000 | 1.2500 | 0.2500 |
| 0.015687 | 1.0000 | 1.5000 | 0.1250 | 0.000061 | 1.0000 | 1.5000 | 0.2500 |
| 0.000005 | 1.0000 | 0.2500 | 0.1250 | 0.000000 | 1.0000 | 0.2500 | 0.3125 |
| 0.000036 | 1.0000 | 0.5000 | 0.1250 | 0.000001 | 1.0000 | 0.5000 | 0.3125 |
| 0.000123 | 1.0000 | 0.7500 | 0.1250 | 0.000003 | 1.0000 | 0.7500 | 0.3125 |
| 0.000290 | 1.0000 | 1.0000 | 0.1250 | 0.000007 | 1.0000 | 1.0000 | 0.3125 |
| 0.000567 | 1.0000 | 1.2500 | 0.1250 | 0.000015 | 1.0000 | 1.2500 | 0.3125 |
| 0.000980 | 1.0000 | 1.5000 | 0.1875 | 0.000025 | 1.0000 | 1.5000 | 0.3125 |
| 0.000001 | 1.0000 | 0.2500 | 0.1875 | 0.000000 | 1.0000 | 0.2500 | 0.3750 |
| 0.000007 | 1.0000 | 0.5000 | 0.1875 | 0.000000 | 1.0000 | 0.5000 | 0.3750 |
| 0.000024 | 1.0000 | 0.7500 | 0.1875 | 0.000002 | 1.0000 | 0.7500 | 0.3750 |
| 0.000057 | 1.0000 | 1.0000 | 0.1875 | 0.000004 | 1.0000 | 1.0000 | 0.3750 |
| 0.000112 | 1.0000 | 1.2500 | 0.1875 | 0.000007 | 1.0000 | 1.2500 | 0.3750 |
| 0.000194 | 1.0000 | 1.3000 | 0.1875 | 0.000012 | 1.0000 | 1.5000 | 0.3750 |

FINISH CONTOUR MILLING - Continued

Finally, equations were developed that described approximate airfoil deflection characteristics. Equations were based on beam theory, and were adapted to give good agreement between calculated deflection, and measured deflection of the model airfoil. Equations are shown in Figure 72 (pg 132). FORTRAN programs were written for the equations and used to calculate airfoil deflection characteristics with normal force applied at the leading edge and at the stacking axis, at all designed sections of the airfoil, with thicknesses 30 and 60 mils above finished airfoil thickness, and with the airfoil rough contour milled to various airfoil extended lengths (distance from the airfoil tip). Typical results are shown in Table 11 (pgs 91-93), together with the FORTRAN program that produced them. Calculated and measured deflection characteristics for conditions that were modeled are shown in Table 12 (pg 94). Comparison of these shows that the equations gave reasonably accurate characteristics.

Control of Airfoil Deflection.

Alternative methods were considered for limiting airfoil deflection during finish contour milling. One was incremental rough and finish contour milling of airfoils. This consisted of rough contour milling an airfoil a short distance down from the tip, then finish contour milling this section of the airfoil. Then a second section would be rough contour milled an additional distance down from the tip, and this section would be finish contour milled. This sequence would be repeated until the full length of the airfoil was finish contour milled.

With this method, the extended length of the airfoil subjected to normal cutting force would be very short, so that the airfoil would be stiffer than if the entire airfoil were first rough contour milled.

Deflection characteristics of the Stage 1 blisk airfoil were calculated for this method. The equations previously described were used for these calculations. Results are shown in Figure 73 (pg 133). Very favorable conditions were used for this analysis, including 8 cutting increments, and a very low normal force of 7.5 pounds. Results show that even under these conditions, steps between increments would be produced that are as great as almost 400 microinches on the airfoil surface at the leading edge, where contour is very critical. Higher normal force was probable, which would make steps even larger, and could cause thickness variations of more than one mil. The cost of removing the roughing cutter 12 times, and replacing it with the finishing cutter the same number of times, would be substantial.

The method which was selected for use is based on supporting airfoils while finish contour milling. Support is provided by the bulk material from which the airfoil is milled while milling one side of the airfoil, and by cast alloy matrix while milling the other side. First a pocket would be rough contour milled between two adjacent airfoils. Then the surfaces of this pocket, which would become the facing sides of the two adjacent airfoils, would be finish contour milled. Next, a low melting temperature alloy would be poured into the pocket using a simple mold. Then pockets on each side of the first would be finished, producing two adjacent airfoils, while the airfoils were supported by the matrix alloy.

It was determined that the cost of the second method would be substantially less than the first, and that it would give adequate support to airfoils, so that thickness would not be significantly affected by deflection from normal cutting force.

TABLE 11

COMPUTER PROGRAM AND CALCULATED ESTIMATES OF BLISK STAGE NO. 1 AIRFOIL LEADING EDGE DEFLECTION PER POUND OF NORMAL FORCE FROM FINISH CONTOUR MILLING

```
100*#RUNH *=(CORE=6)
110 2 FORMAT (4X,F10.6,14X,F6.3,4X,F6.3)
120 3 FORMAT (21X,7HDEFLC60,11X,2HEL,9X,1HH,10X,7HSECTION)
140 WRITE (6,3)
150 EL =0.0
160 DO 30 I= 1,200
170 EL=EL+.150
177 IF(EL .GT. .900)GOTO 99
180 H = (.0096+.064*EL)*.060
190 Z1 = (1.414*EL)*3.E7*((H/2.)**3)
200 DEFLC60=7.*((.707*EL)**3)/Z1
210 IF (DEFLC60 .GE. 10.E-6)GOTO 8
230 GOTO 30
235 8 WRITE(6,4) DEFLC60,EL,H
236 IF (DEFLC60 .GE. 200.E-6) GOTO 99
250 30 CONTINUE
260 99 STOP
270 END
```

DEFLC60 = Calculated Deflection of the Airfoil Corner Having .030" of Material Remaining on Each Side for Finish Contour Milling - Inches/Pound of Normal Force

EL = Extended Length, of the Rough Machined Airfoil, Above the Blade Section Defined on the Drawing - Inches.

H = A Computed Thickness of the Roughed Out Airfoil Based on Blade Taper - Inches.

```
ready
*RUN
```

| DEFLC60 | EL | H | SECTION K-K |
|---|---|---|---|
| 0.000021 | 0.150 | 0.079 | |
| 0.000060 | 0.300 | 0.089 | |
| 0.000099 | 0.450 | 0.098 | |
| 0.000133 | 0.600 | 0.108 | |
| 0.000161 | 0.750 | 0.118 | |
| 0.000184 | 0.900 | 0.127 | |

```
*180 H=(.0104+.067*EL)+.060
*RUN
```

| DEFLC60 | EL | H | SECTION J-J |
|---|---|---|---|
| 0.000020 | 0.150 | 0.080 | |
| 0.000057 | 0.300 | 0.091 | |
| 0.000093 | 0.450 | 0.101 | |
| 0.000124 | 0.600 | 0.111 | |
| 0.000149 | 0.750 | 0.121 | |
| 0.000169 | 0.900 | 0.131 | |

```
*180 H=(.0108+.070*EL)+.060
*RUN
```

| DEFLC60 | EL | H | SECTION H-H |
|---|---|---|---|
| 0.000020 | 0.150 | 0.081 | |
| 0.000054 | 0.300 | 0.092 | |
| 0.000088 | 0.450 | 0.102 | |
| 0.000117 | 0.600 | 0.113 | |
| 0.000140 | 0.750 | 0.123 | |
| 0.000158 | 0.900 | 0.134 | |

TABLE 11 - Continued

```
*170 EL=EL+.150
*180 H=(.0116+.073*EL)+.060
*RUN
```

| DEFLC60 | EL | H | SECTION G-G |
|---|---|---|---|
| 0.000019 | 0.150 | 0.083 | |
| 0.000051 | 0.300 | 0.094 | |
| 0.000083 | 0.450 | 0.104 | |
| 0.000109 | 0.600 | 0.115 | |
| 0.000130 | 0.750 | 0.126 | |
| 0.000146 | 0.900 | 0.137 | |

```
*170 EL=EL+.200
*180 H=(.0127+.078*EL)+.060
*RUN
```

| DEFLC60 | EL | H | SECTION F-F |
|---|---|---|---|
| 0.000027 | 0.200 | 0.088 | |
| 0.000067 | 0.400 | 0.104 | |
| 0.000098 | 0.600 | 0.120 | |
| 0.000121 | 0.800 | 0.135 | |

```
*180 H = (.0146+.083+ at *EL)+.060
*RUN
```

| DEFLC60 | EL | H | SECTION E-E |
|---|---|---|---|
| 0.000025 | 0.200 | 0.091 | |
| 0.000060 | 0.400 | 0.108 | |
| 0.000087 | 0.600 | 0.124 | |
| 0.000107 | 0.800 | 0.141 | |

```
*180 H(.0170+.087*EL)+.060
*RUN
```

| DEFLC60 | EL | H | SECTION D-D |
|---|---|---|---|
| 0.000022 | 0.200 | 0.094 | |
| 0.000053 | 0.400 | 0.112 | |
| 0.000078 | 0.600 | 0.129 | |
| 0.000095 | 0.800 | 0.147 | |

```
*180
```

TABLE 11 - Continued

```
*180 H=(.0194+.094*EL)+.060
*RUN
```

| DEFLC60 | EL | H | |
|---|---|---|---|
| 0.000020 | 0.200 | 0.098 | SECTION C-C |
| 0.000047 | 0.400 | 0.117 | |
| 0.000067 | 0.600 | 0.136 | |
| 0.000081 | 0.800 | 0.155 | |

```
*180 H=(.0251+.123*EL)+.060
*RUN
```

| DEFLC60 | EL | H | |
|---|---|---|---|
| 0.000014 | 0.200 | 0.110 | SECTION B-B |
| 0.000031 | 0.400 | 0.134 | |
| 0.000042 | 0.600 | 0.159 | |
| 0.000048 | 0.800 | 0.184 | |

TABLE 12
STATIC DEFLECTION OF STAGE 1 BLISK MODELED AIRFOIL

| Location | Extended Length (in) | Test No. | Deflection (in/lb) Calculated | Tested |
|---|---|---|---|---|
| BLISK AIRFOIL CAST IN MATRIX | | | | |
| At leading edge corner | .240 | 1 | .00136 | .00110 |
| At leading edge corner | .400 | 2 | .00159 | .00170 |
| At stack axis | .240 | 3 | .00011 | .00012 |
| At stack axis | .400 | 4 | .00030 | .00028 |
| BLISK AIRFOIL MODEL | | | | |
| At leading edge corner | .400 | 5 | .00160 | .00150 |
| At stack axis | .400 | 6 | .00029 | .00026 |
| AIRFOIL MODEL +0.060-INCH THICKNESS | | | | |
| At leading edge corner | .240 | 9 | .000149 | .000170 |
| At leading edge corner | .400 | 10 | .000225 | .000210 |
| At stack axis | .240 | 11 | .000028 | .000028 |
| At stack axis | .400 | 12 | .000073 | .000036 |
| AIRFOIL MODEL +0.030-INCH THICKNESS WITH 0.160-INCH OF FINISHED BLADE EXTENDING BEYOND WEIGHTED POINT | | | | |
| At lead edge | .240 | 13 | .000141 | .000065 |
| At stack axis | .240 | 14 | .000026 | .000015 |
| SAME AS ABOVE EXCEPT 0.160-INCH OF FINISHED BLADE MACHINED OFF | | | | |
| At leading edge | .240 | 15 | .000141 | .000070 |
| At stack axis | .240 | 16 | .000026 | .000013 |

NOTE:See Figure 71 (pg 131) for Test Setup.

FINISH CONTOUR MILLING - Continued
Process Control

Airfoil thickness, produced by finish contour milling, is dependent on cutter runout which was determined by the combined effects of machine spindle and cutter holder runout, as well as by clearance between the cutter shank and the holder bore, and the concentricity of the cutter cutting edges relative to the cutter shank. Airfoil thickness is dependent on the manufactured geometry of cutters, and changes in geometry as the cutter wears. Furthermore, airfoil thickness is dependent on cutter deflection, which changes as cutter geometry changes as the result of wear. All of these factors are variables, and therefore, cause airfoil thickness to vary. It is necessary to control their influence on airfoil thickness, in order to maintain thickness within the design limits of +4 to -3 mils from nominal.

A method for attaining this control was devised that utilizes a test block which is milled with each finish contour milling cutter immediately before it is used to mill airfoils. Milling of the test block is done with the block held in a special vise on the 5-axis milling machine adjacent to the machine's B-axis table on which a blisk is placed for airfoil milling. Since the machine has four tables, to allow machining four identical blisks at a time, four separate vises are needed to hold four separate test blocks, all of which are milled simultaneously by four separate cutters.

Numerical control programs were developed to mill test blocks with each type of finish contour milling cutter. Milling is done on two opposite sides of a test block, under cutting conditions which are as much like those used to mill airfoils as possible. The test block is made of the same alloy as the airfoils. Therefore, the thickness of the test block between the two milled sides is dependent on the same factors upon which the airfoil thickness is dependent. By milling and measuring a test block, the influence of these factors on airfoil thickness can be predicted. The test block arranagement is shown in Figure 74 (pg 134).

After the development machine became available, test block thickness was correlated with airfoil thickness. A correlation analysis is shown in Figure 75 (pg 135). Limits were established for test block thickness to obtain control over airfoil thickness variability resulting from the combined effects of cutter runout, cutter manufactured geometry, changes in geometry through cutter wear, and changes in cutter deflection. For example, limits for test block thickness could be set that would provide for a test block thickness spread of 3 mils; consequently the influence of these factors on airfoil thickness spread would be limited to 3 mils out of a total airfoil design tolerance spread of 7 mils.

Surface Texture

Microscopic examination was made of finish contour milled surfaces under a variety of cutting conditions. A typical surface is shown in Figure 76 (pg 136). The number of times the visible pattern repeats over a distance of an inch, called the pattern frequency, is given by the equation:

$$F = \frac{N}{V} \qquad \text{(Eq 3)}$$

FINISH CONTOUR MILLING - Continued

where F = pattern frequency (repeats per inch)
N = cutter speed (rpm)
V = feed rate (in/min)

The pattern frequency was therefore the same as would be produced by a cutter with a single tooth. This indicates that it was produced by the tooth which has the largest cutting radius. If cutter geometry and runout could be better controlled than for the test which produced the pattern shown, the frequency would be greater.

Roughness of the surface shown was about 60 microinches average amplitude measured perpendicular to the path of the cutter, and roughly half of this measured parallel to the cutter path. This roughness had been found to be within the capability of abrasive flow machining to produce the final roughness of 32 microinches average amplitude required for airfoils. Consequently, the single tooth cutting pattern did not appear to have significant disadvantage.

Finish Contour Milling with the Development Machine

As soon as the development machine became available, airfoils and platforms were rough and finish contour milled using previously developed NC programs. Finish contour milling frequently produced waves on airfoil surfaces. It was hypothesized that this could be the result of irregular cutting caused by the inability of all teeth on cutters having 24 teeth to actually cut chips. Excessive waviness was eliminated by reducing the number of teeth to 12 on all finish contour milling cutters.

Maximum lineal feed rate of which the machine was capable without instability was determined by milling trials at various feed rates. The cutting speeds for each type of cutter were selected by milling over a range of speeds, and selecting the speeds that gave the lowest surface roughness. Results of typical tests are given in Table 13 (pg 97). It was also necessary to consider the influence of speed on airfoil thickness. Typical effects are shown in Table 14 (pg 97); the effect of speed on thickness is shown under the column heading First Cycle, and the contribution of deflection to thickness is approximately indicated under the column heading Thickness Change.

In general, the maximum lineal feed rate used was 15 in/min. However, milling trials were made at feed rates up to 30 in/min. They showed that milling should be feasible at least to this rate, if the milling machine were capable of reliable positioning performance.

Milled geometry of airfoils was measured, and NC program changes were made to adjust geometry to conform as closely as possible to design limits. Milled airfoils were abrasive flow machined (AFM) and then measured, after which NC program adjustments were made to produce airfoil chord lengths that allowed for reductions produced by AFM.

TABLE 13
RELATIONSHIP BETWEEN CUTTING SPEED AND SURFACE ROUGHNESS FOR STAGE 5 BLISK AIRFOILS MILLED WITH DEVELOPMENT MACHINE

| Test and Conditions | Cutting Speed* (rpm) | Cutting Speed* (sft/min) | Surface Roughness Average Amplitude Convex | Surface Roughness Average Amplitude Concave |
|---|---|---|---|---|
| TEST SERIES NO. 1 | 2,000 | 98 | 72 | |
| | 3,000 | 147 | 74 | |
| Material - 17-4PH | 4,000 | 196 | 84 | |
| | 4,500 | 220 | 93 | |
| Lineal Feed - 18 in/min | 5,000 | 245 | 71 | |
| | 6,000 | 294 | 100 | |
| Cutter - 3/16 finish, | 8,000 | 391 | 81 | |
| 12 teeth | 10,000 | 489 | 88 | |
| TEST SERIES NO. 2 | 2,000 | 98 | 47 | 65 |
| | 2,500 | 122 | 92 | 88 |
| Material - AM355 | 3,000 | 147 | 51 | 46 |
| | 3,500 | 171 | 74 | 62 |
| Lineal Feed - 18 in/min | 4,000 | 196 | 73 | 56 |
| | 4,500 | 220 | 72 | 86 |
| Cutter - 3/16 finish, | 5,000 | 245 | 98 | 88 |
| 12 teeth | | | | |

* Optimum speed from above results - 3,000 rpm = 145 sft/min

TABLE 14
CHANGES IN TEST BLOCK THICKNESS AND IN AIRFOIL FINISH CONTOUR MILLING CUTTER DEFLECTION WITH CHANGES IN CUTTING SPEED

| Cutting Speed (rpm) | Thickness (in) 1st Cycle | Thickness (in) 3rd Cycle | Thickness Change (in) |
|---|---|---|---|
| 6,200 | .4582 | .4563 | .0019 |
| 4,500 | .4584 | .4565 | .0019 |
| 3,300 | .4593 | .4572 | .0021 |
| 2,600 | .4600 | .4572 | .0028 |
| 1,900 | .4602 | .4574 | .0028 |
| *2,600 | .4603 | .4574 | .0029 |
| *6,200 | .4583 | .4564 | .0019 |
| *6,200 | .4583 | .4564 | .0019 |

*Tests repeated for accuracy check.

Cutter: 12 teeth, 5/16 truncated ball end, 883 carbide.
Extension: 2 inches from "full ball" end to holder.
Feed Rate: 15 in/min.

FINISH CONTOUR MILLING - Continued

Most of this development work was done with blisk blanks made of 17-4PH alloy, which has machining characteristics similar to AM355 alloy of which actual blisks are made. This was done because the cost of the alloy used was far lower than the cost of the blisk alloy.

Finally, several airfoils and platforms of each type were milled, and finished with AFM and very minor benching, to demonstrate that the overall process was sufficiently developed to produce the first complete blisks. These were milled on AM355 alloy blisk blanks.

Finish Contour Milling Cutter Wear

The wear of airfoil finish contour milling cutters combined with the influence that wear has on cutter deflection, was investigated during milling development with the 5-axis NC machine. Test block thickness was used to obtain information on how wear affects airfoil thickness. Examples of such information are given in Figure 77 (pg 137) and Table 15 (pg 99).

The relationship of wear to the width of the land on the edge of each cutter tooth before the cutter was used, was also investigated to determine if land width significantly influences wear. Results are shown in Figure 78 (pg 138) and Table 16 (pg. 100). Cutter A1 used in this test wore one mil as indicated by test block thickness, while cutting one Stage 4 pocket. It had only five lands that were three mils wide before use. In contrast, Cutter A5 in Table 15 (pg 99) wore three mils as indicated by test block thickness, while milling six pockets. It had 8 lands that were at least 3 mils wide before use. These data suggest that land width should not be less than 3 mils on unused cutters.

Cutter wear was allowed to progress beyond established limits while milling the last 14 airfoils and platforms on the Stage 3 blisk to determine effects on airfoil thickness and the trend of the increase in cutter wear. Results are shown in Table 15.

It was concluded that cutter life in production might be doubled, to reduce usage by one half. This improvement might be obtained by close control of new cutter land width to an optimum value, such as 3 mils, and by allowing cutter wear as indicated by test block thickness to progress further. The effect on airfoil thickness of allowing cutter wear to progress further, would have to be investigated to determine if it would be acceptable.

TABLE 15
FINISH CONTOUR MILLING CUTTER USAGE FOR MILLING AIRFOILS AND PLATFORMS WITH DEVELOPMENT MACHINE ON STAGES 3 AND 4 BLISK FOR ENGINE TESTING

| Operation | Stage | Cutter | Total No. of Pockets Milled | Test Block Thickness (mils)* Min | Max | Change |
|---|---|---|---|---|---|---|
| Airfoils | 4 | A1 | 1 | 473 | 474 | 1 |
| | | A2 | 6 | 471 | 471 | 0 |
| | | A3 | 3 | 472 | 474 | 2 |
| | | A4 | 4 | 471 | 472 | 1 |
| | | A5 | 6 | 471 | 474 | 3 |
| | | A6 | 2 | 473 | 474 | 1 |
| | | A7 | 2 | 472 | 473 | 1 |
| | | A8 | 3 | 473 | 474 | 1 |
| | | A9 | 1 | 473 | 473 | 0 |
| | 3 | A10 | 14 | 472 | 473 | 1 |
| | | A11 | 1 | 474 | 474 | 0 |
| | | A3 (Reused) | 13 | 474 | 474 | 0 |
| Platforms | 4 | P1 | 2 | 467 | 468 | 1 |
| | | P2 | 7 | 467 | 468 | 1 |
| | | P3 | 5 | 466 | 468 | 2 |
| | | P4 | 6 | 466 | 468 | 2 |
| | | P5 | 7 | 467 | 468 | 1 |
| | | P6 | 1 | 468 | 468 | 0 |
| | | P7 | 9 | 466 | 468 | 2 |
| | | P8 | 3 | 467 | 468 | 1 |
| | | P9 | 2 | 467 | 469 | 2 |
| | | P7 (Reused) | 10 | 468 | 468 | 0 |
| | | P8 (Reused) | 4 | 468 | 469 | 1 |

*Normal Test Block Thickness Limits (mils): Airfoil 471-474, Platform 465-468. Stage 4 data is given above Stage 3 data since Stage 4 was milled first.

TABLE 16
CHANGE IN LAND WIDTH OF FLUTES ON FINISH CONTOUR MILLING CUTTER AS A RESULT OF WEAR

| Flute No. | Land Width Before Cutting (in) | Land Width After Cutting 1 Pocket (in) |
|---|---|---|
| 1 | +.0006 | +.001 |
| 2 | +.0013 | +.002 |
| 3 | +.0005 | +.002 |
| 4 | +.0006 | +.0025 |
| 5 | +.004 | +.0035 |
| 6 | +.003 | +.0008 |
| 7 | Groove | +.0025 |
| 8 | +.005 | +.004 |
| 9 | +.0065 | +.0065 |
| 10 | +.004 | +.004 |
| 11 | Groove | +.003 |
| 12 | +.0006 | +.0015 |

Cutter - 5/16 inch airfoil finish cutter No. A1. (see Table 15),
Pockets Cut - Stage 4, 1 Pocket.

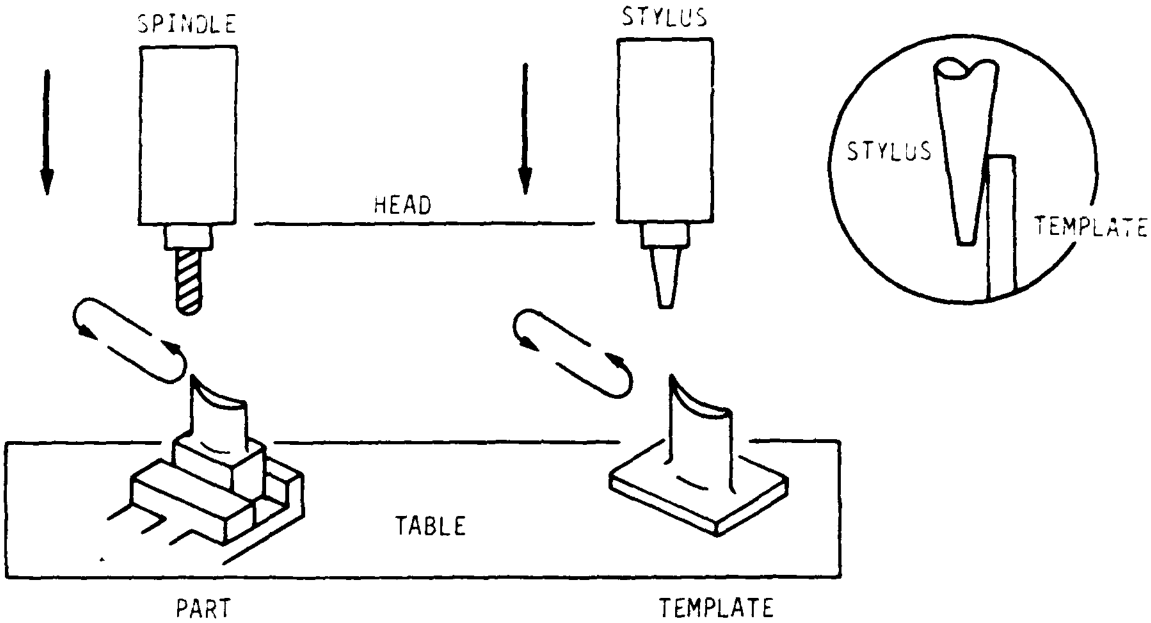
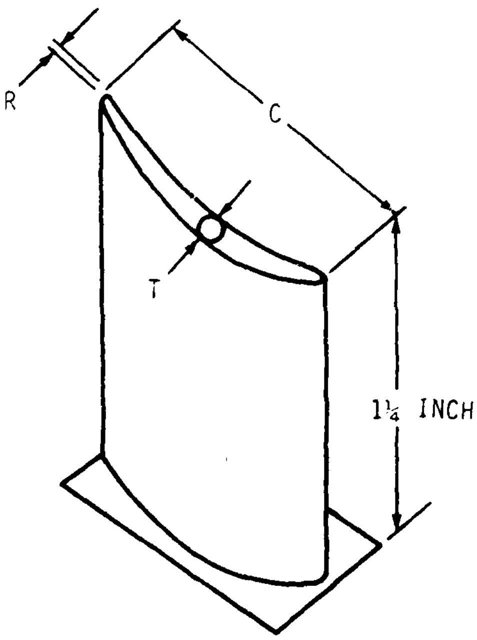



Figure 40. Tracer Milling Test Arrangement.




| | TIP (INCHES) | ROOT (INCHES) |
|---|---|---|
| C | 1.185 | 1.250 |
| T | .055 | .118 |
| R | .005 | .020 |

MATERIAL AM355

HARDNESS RC 39 TO 40

Figure 41. Tracer-Miller Simulated Stage 2 Airfoil.

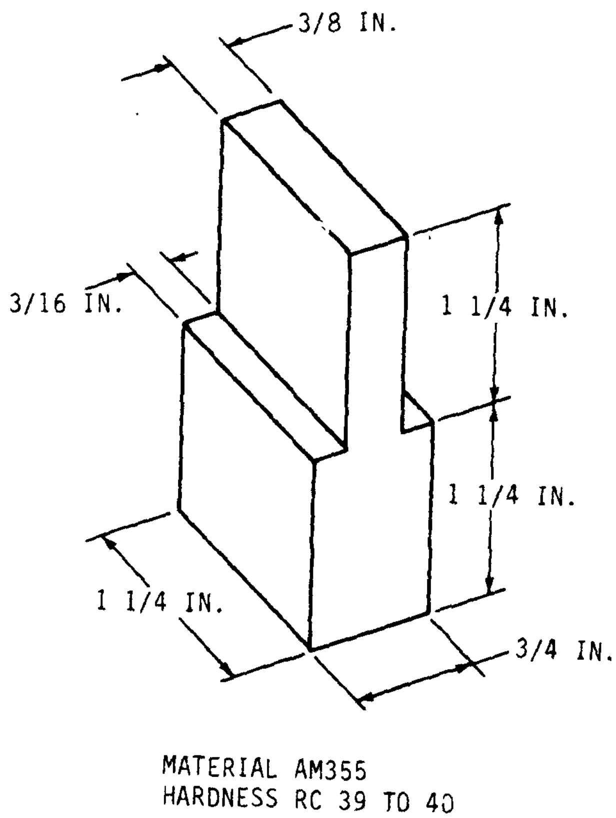



Figure 42. Test Piece Prior to Tracer Milling.

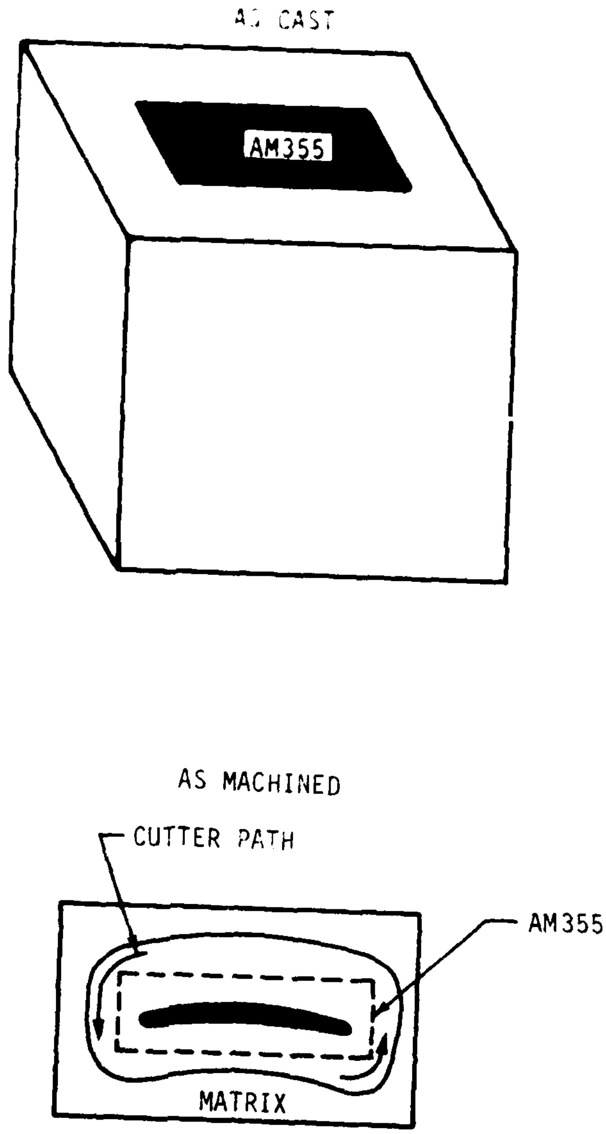



Figure 43. Matrix Supported Test Piece Prior to Tracer Milling.

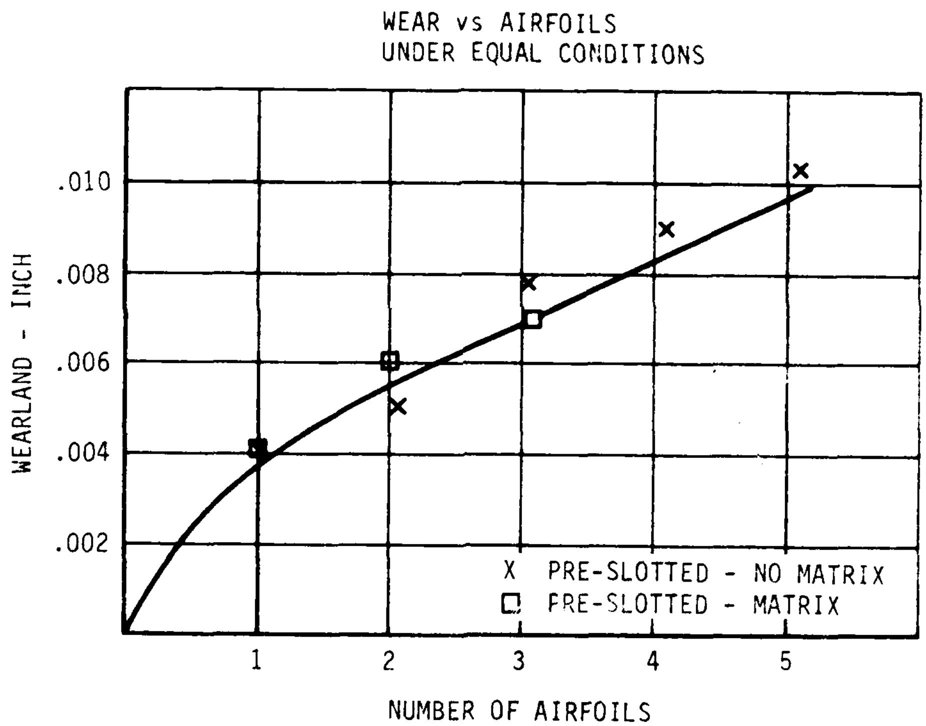



Figure 44. Machining Simulated Airfoil.

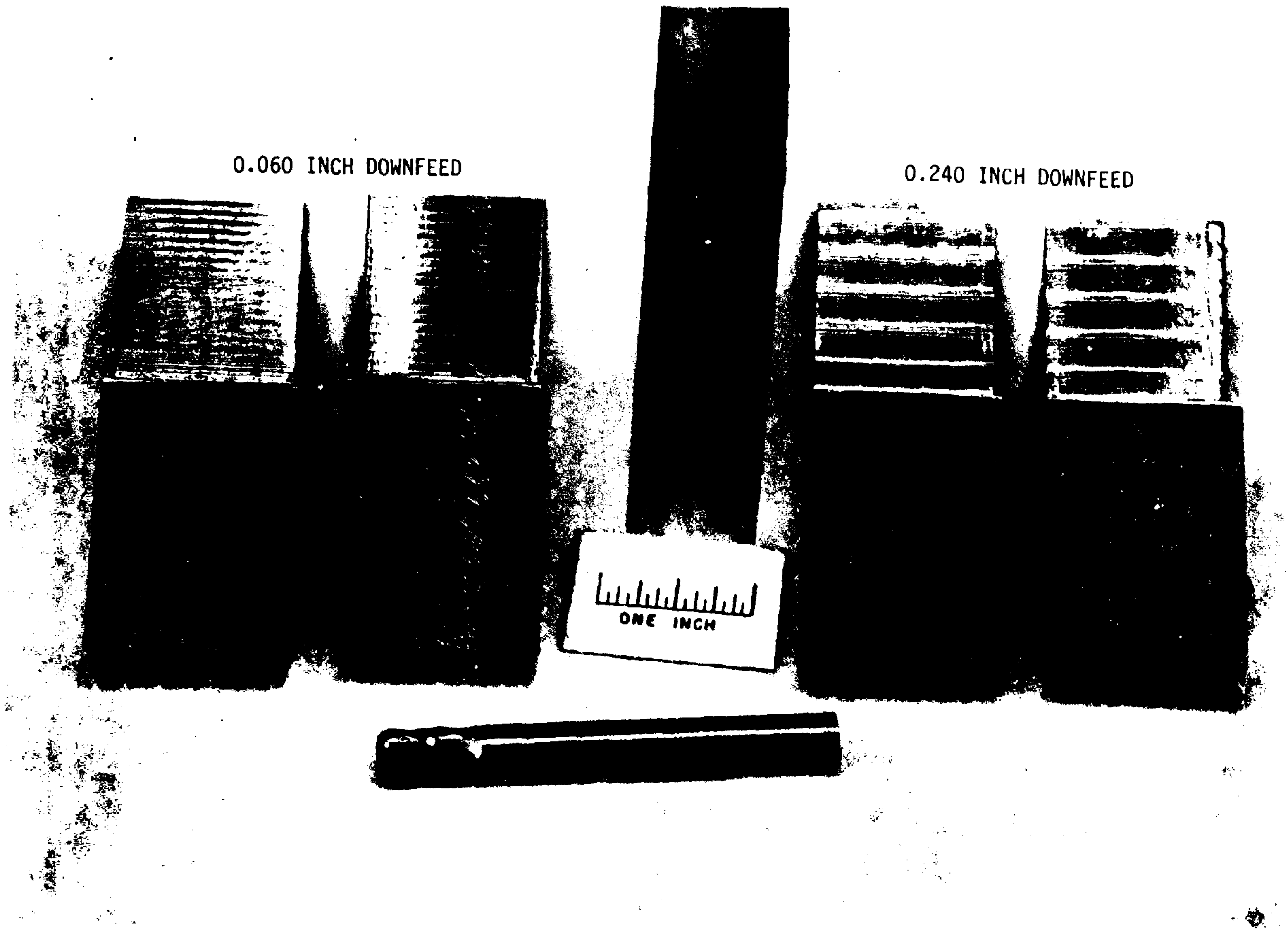
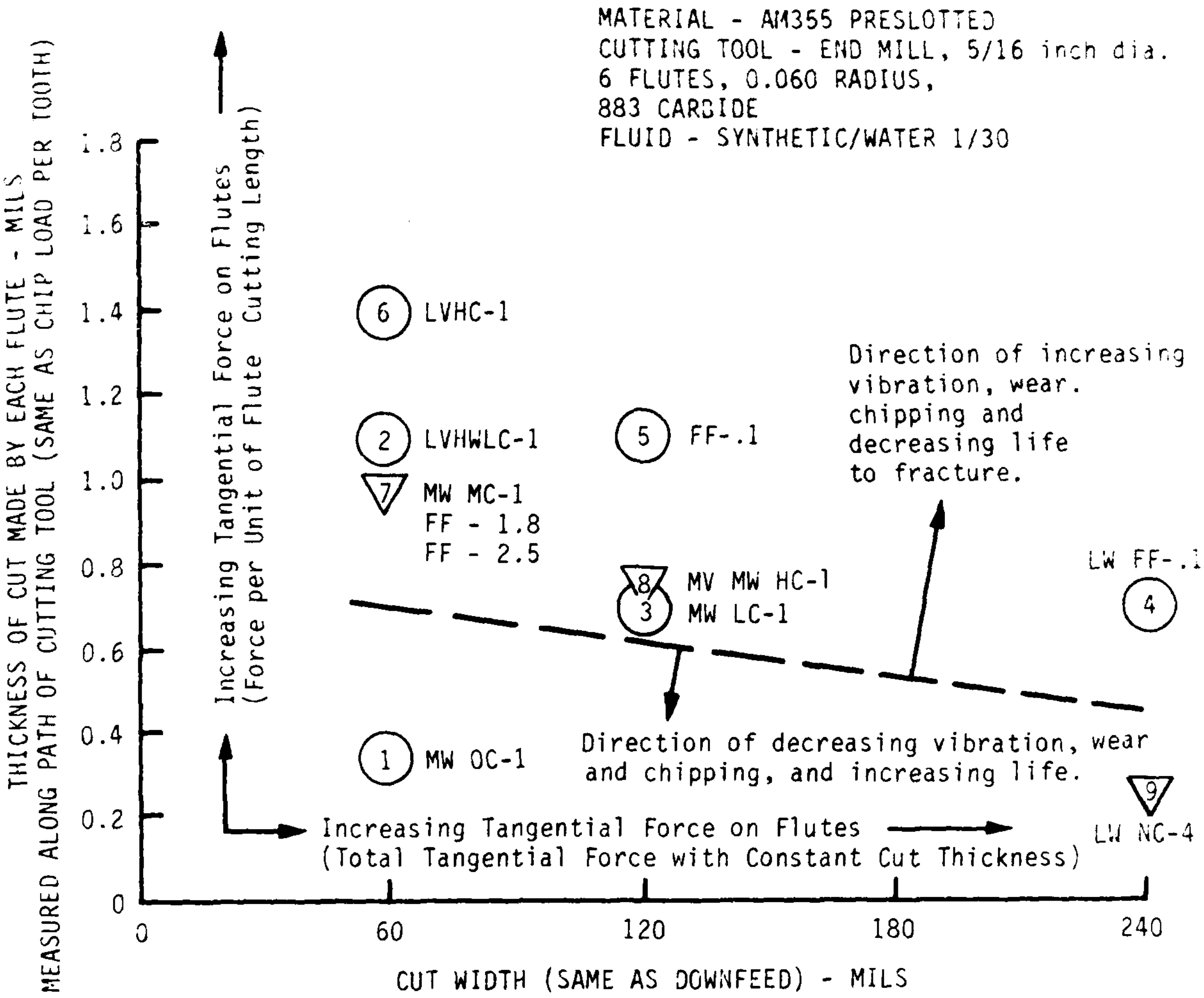



Figure 45. Simulated Airfoils By 3-Axis NC Contour Milling.




SYMBOLS

| | | | | |
|---|---|---|---|---|
| Test Number | - | O 117 sft/min | △ 167 sft/min. | HW: Heavy Wear. |
| Wear | - | LW: Light Wear. | MW: Moderate Wear. | HC: Heavy Chipping. |
| Chipping | - | LC: Light Chipping. | MC: Moderate Chipping. | OC: No Chipping. |
| Vibration | - | LV: Light Vibration. | MV: Moderate Vibration. | NC: Negligible Chipping. |
| Flute Fracture | - | FF: | | |
| Airfoils Cut | - | Number following wear, chipping and fracture symbols. | | |

Figure 46. Analysis of Test Results NC Rough Contour Milling of Simulated Blisk Airfoils.

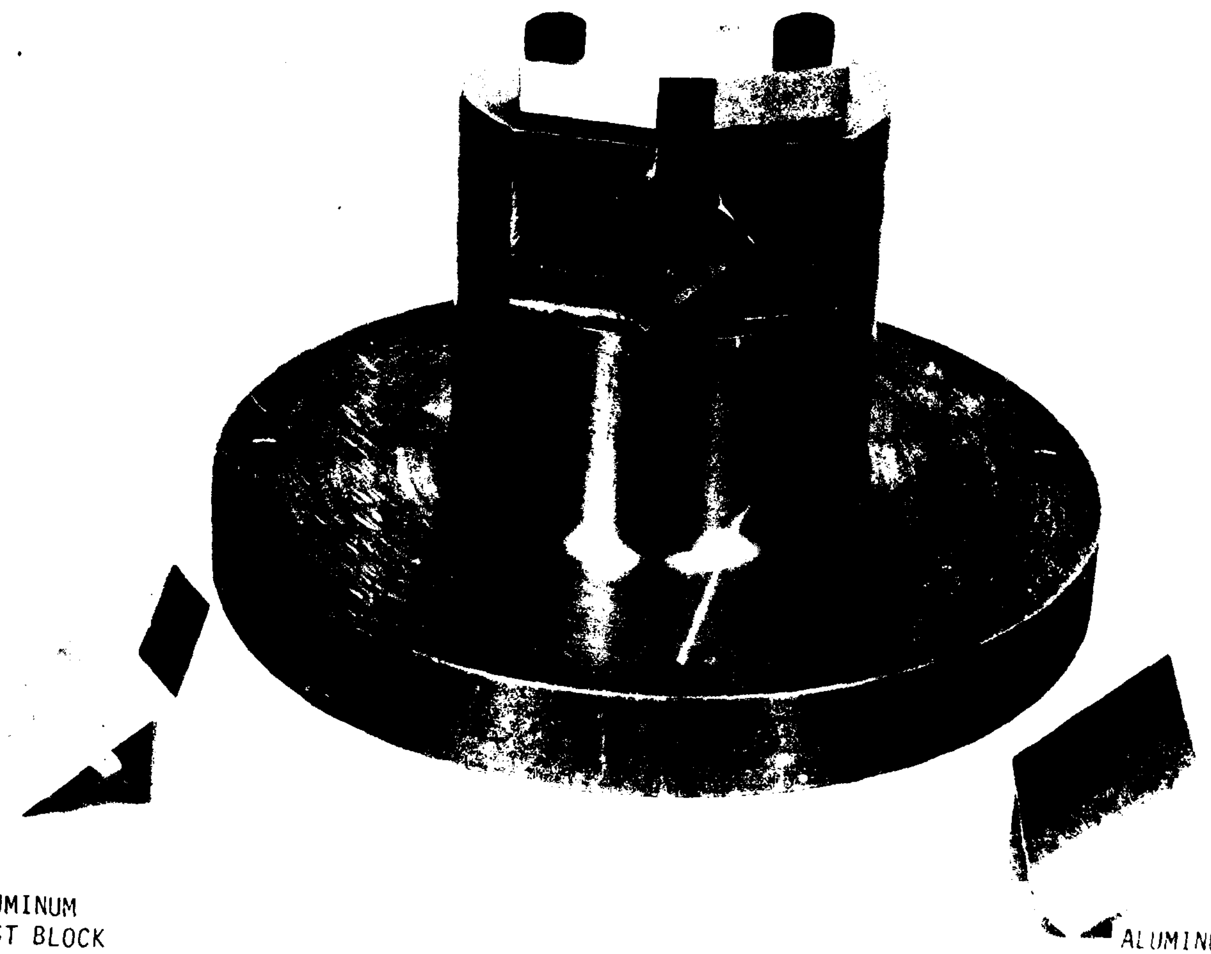



Figure 47. Holding Fixture with AM355 Test Block Mounted.

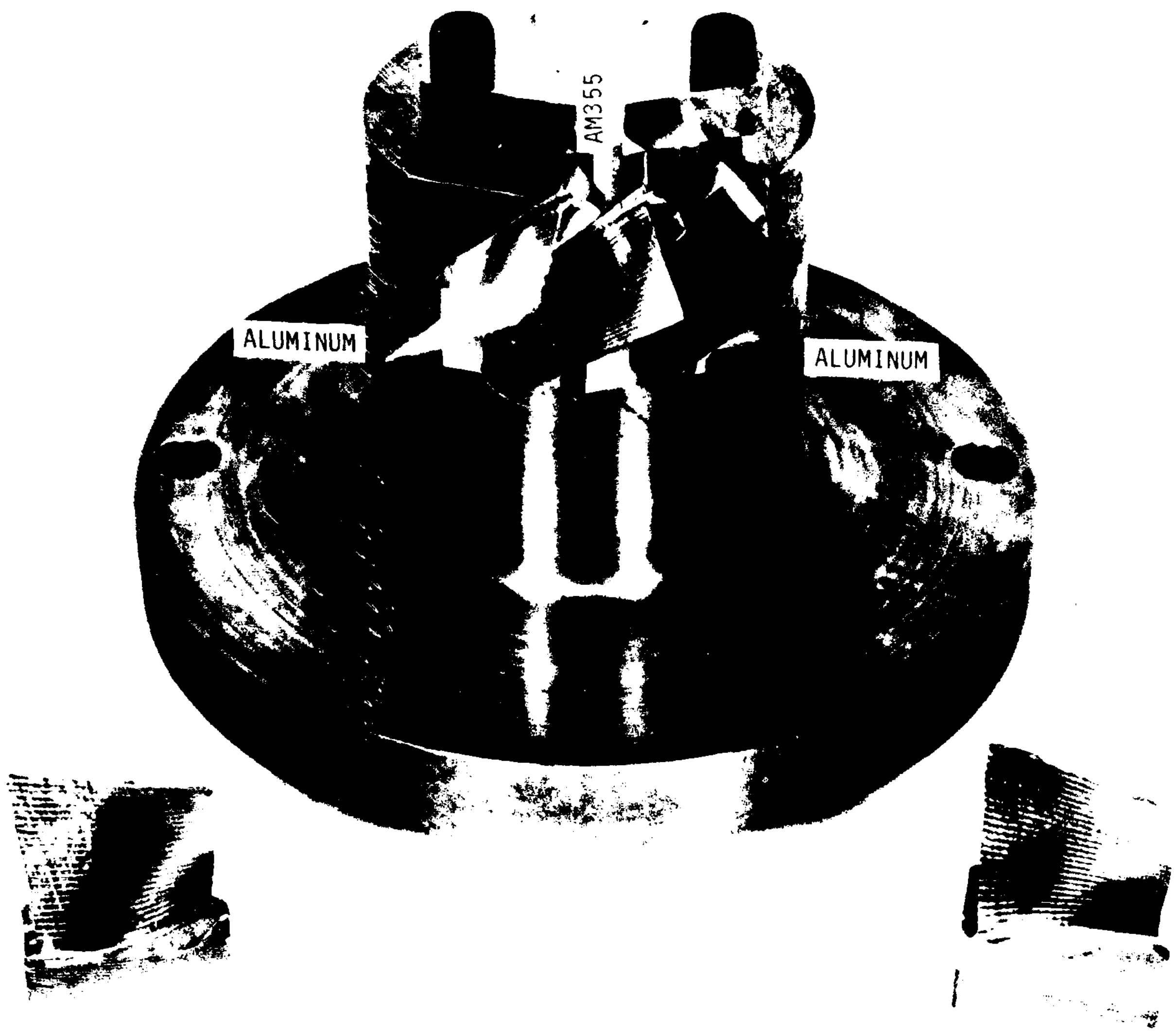



Figure 48. Holding Fixture With Rough Contour Milled Airfoils.

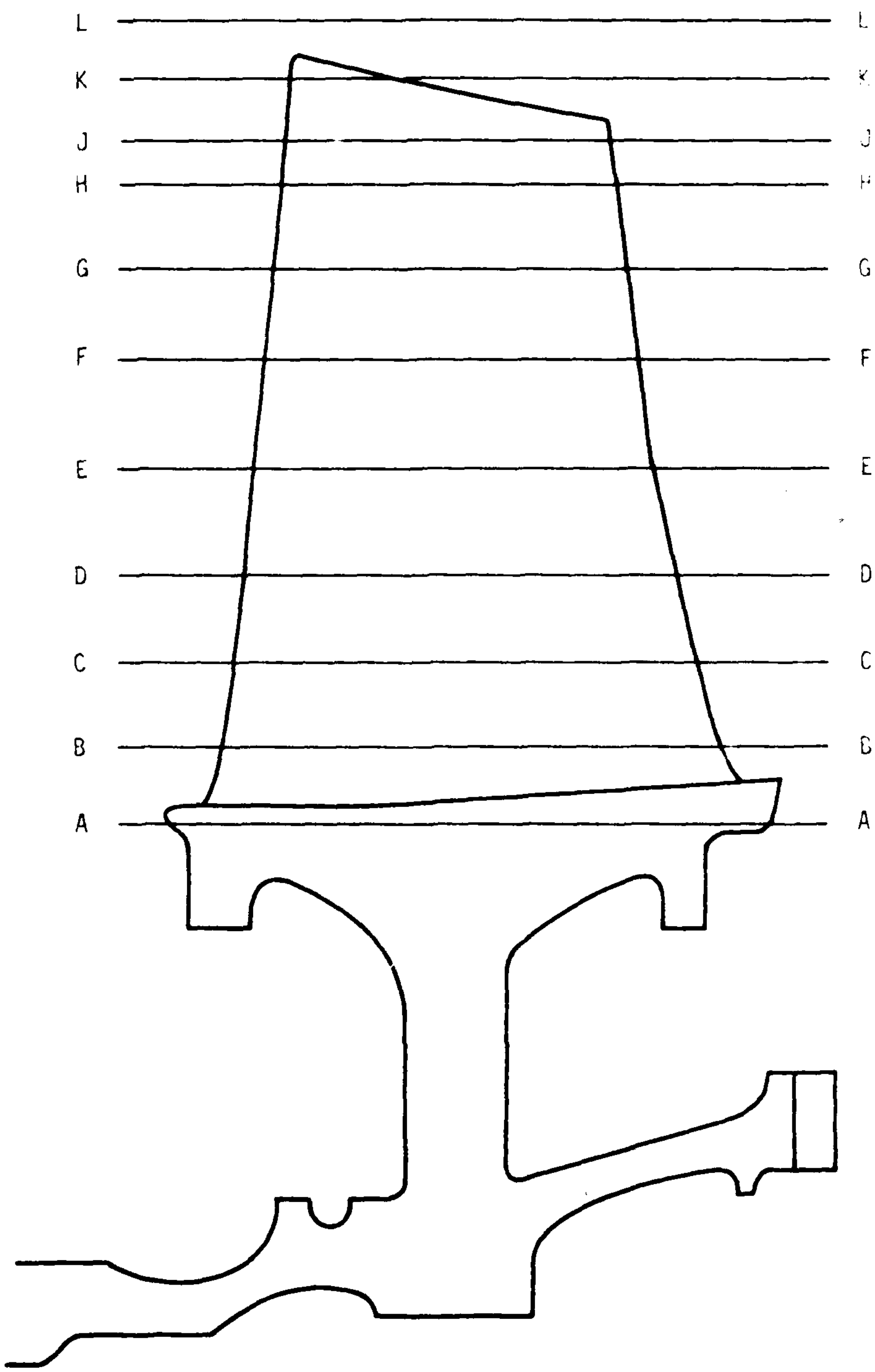



Figure 49. Stage 1 Blade With Sections as Defined on Engineering Drawing.

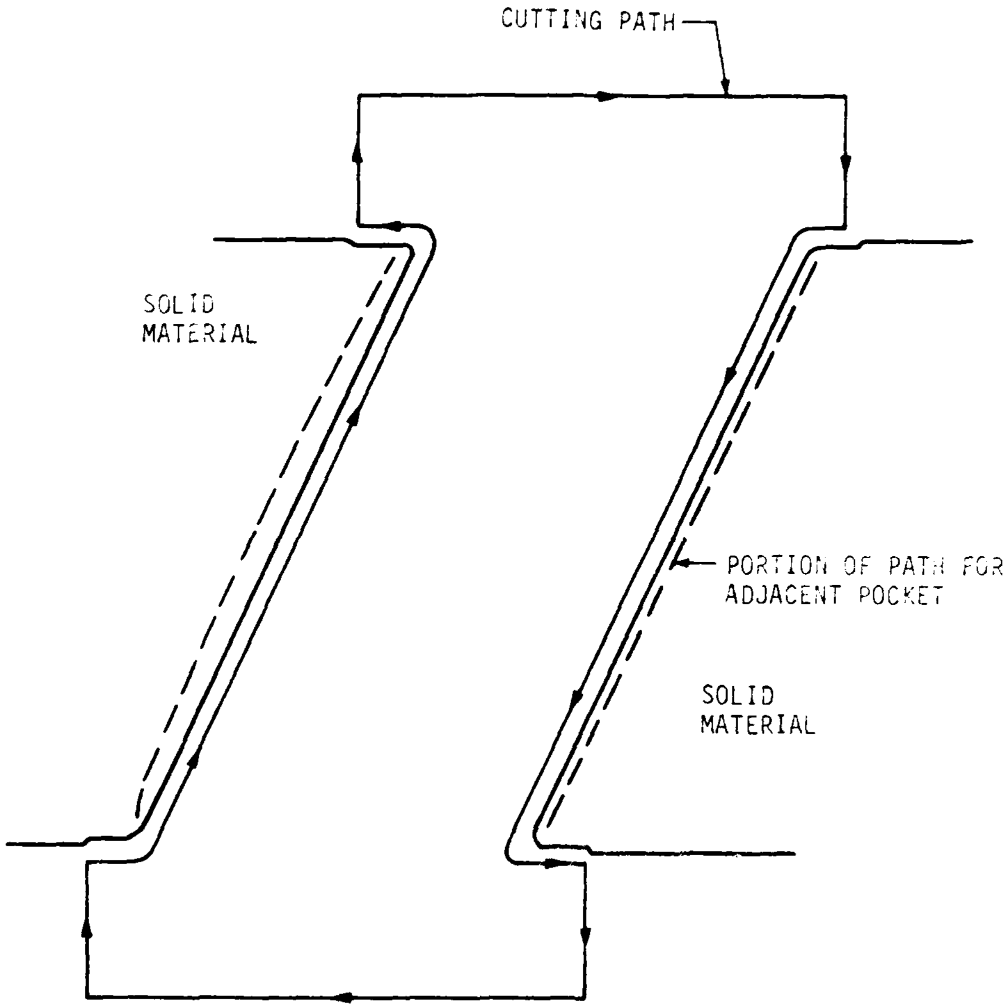



Figure 50. Cutting Path for Airfoil Rough and Finish Contour Milling.

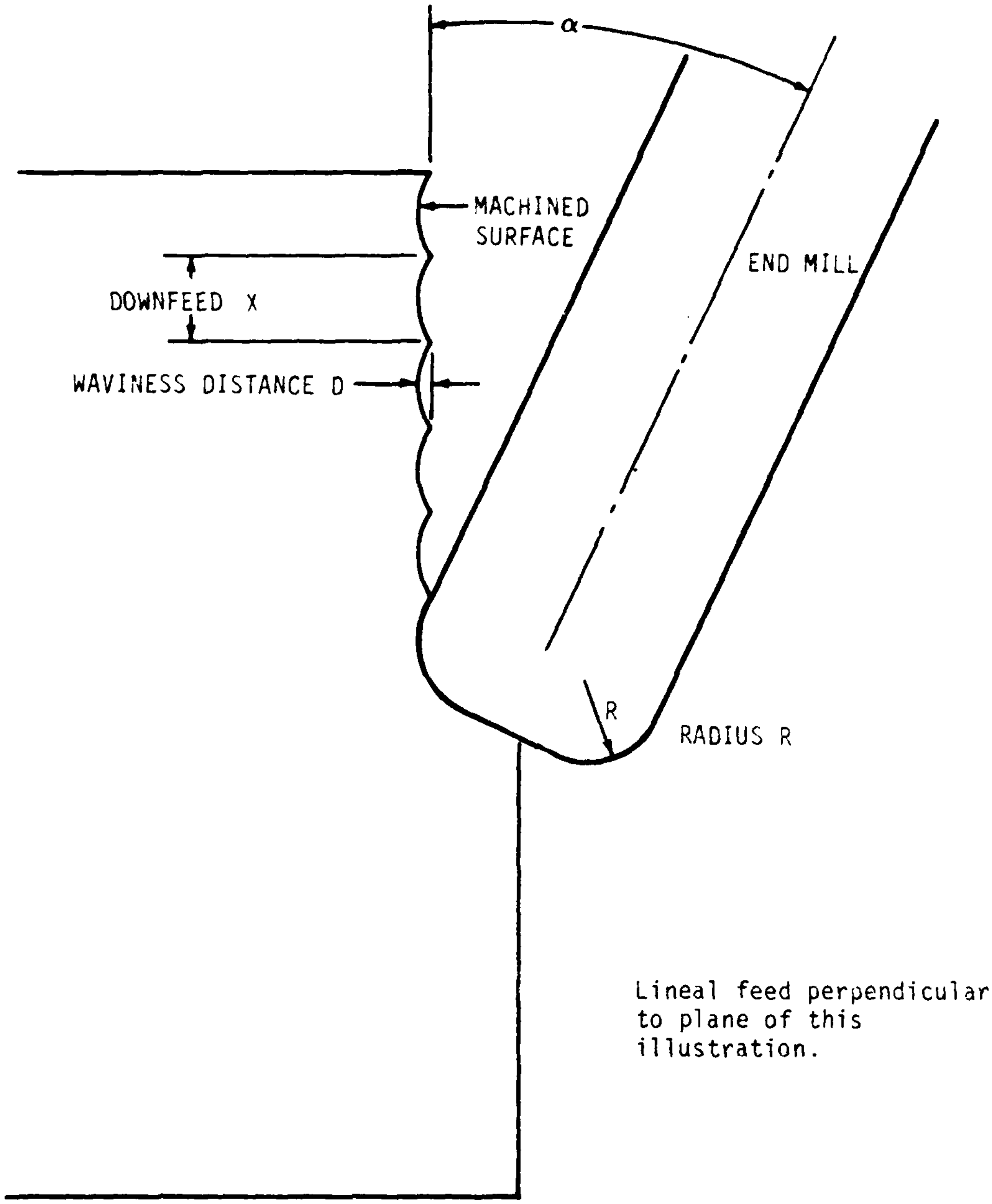



Figure 51. Illustration of Surface Waviness Produced by End Mill at Small Angle to Plane of Machined Surface.

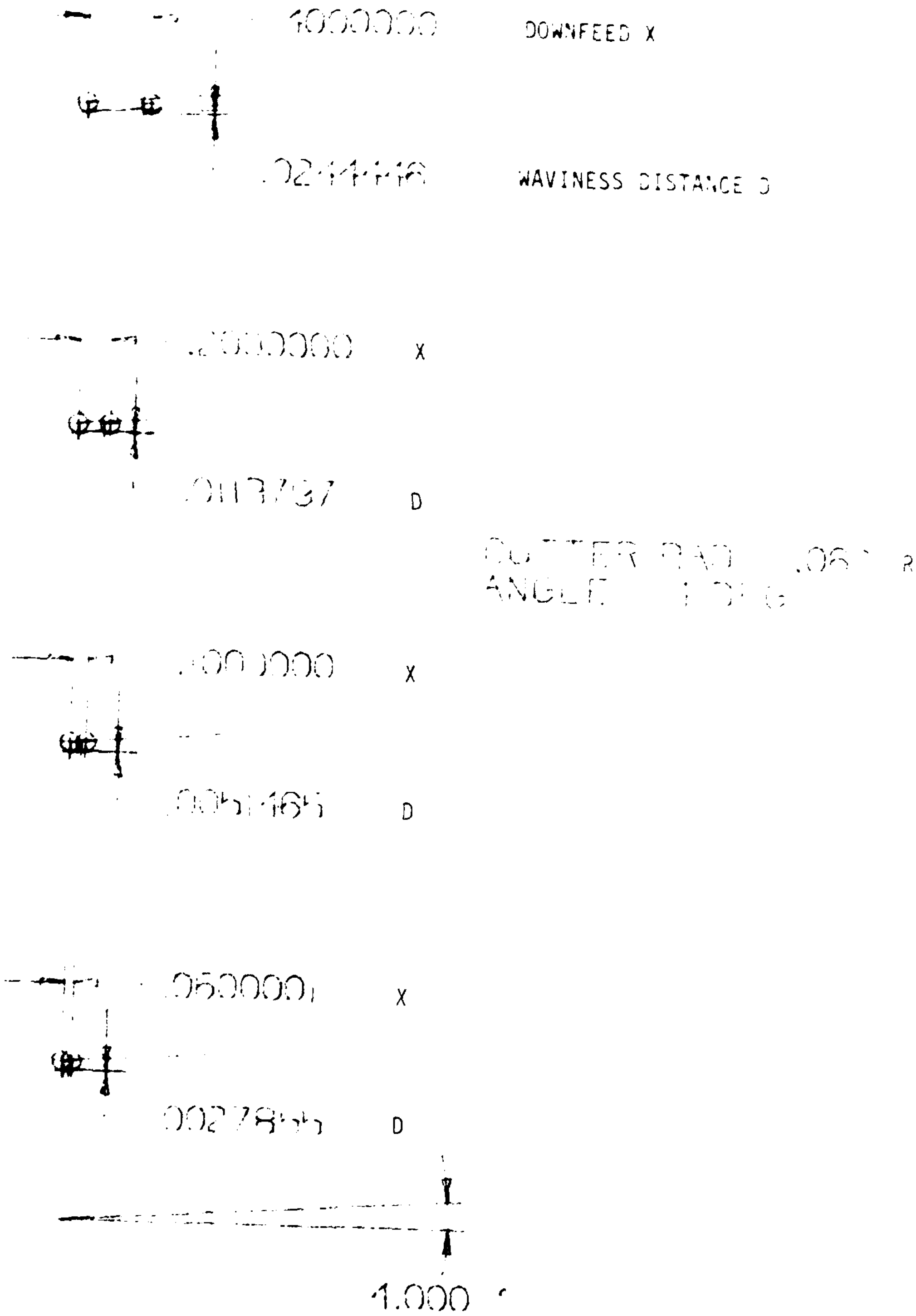



Figure 52. Computer Drawn Analysis of Influence of Downfeed on Surface Waviness With 4 Degrees of Cutter Axis to Plane of Machined Surface and 0.060 Inch Cutter Radius, With Peak to Valley Distance Computed.

CARBIDE GRADE - 883

| | |
|---|---|
| Number of Flutes: | 6 |
| Flute Helix: | 30 degrees right hand spiral |
| Flute to Flute Variance: | .0005 inch max |
| Cylindrical Margin on OD and Radius: | .002 - .003 inch |
| Rake Angle: | 0 degree |
| Relief Angle: | 6 degrees |

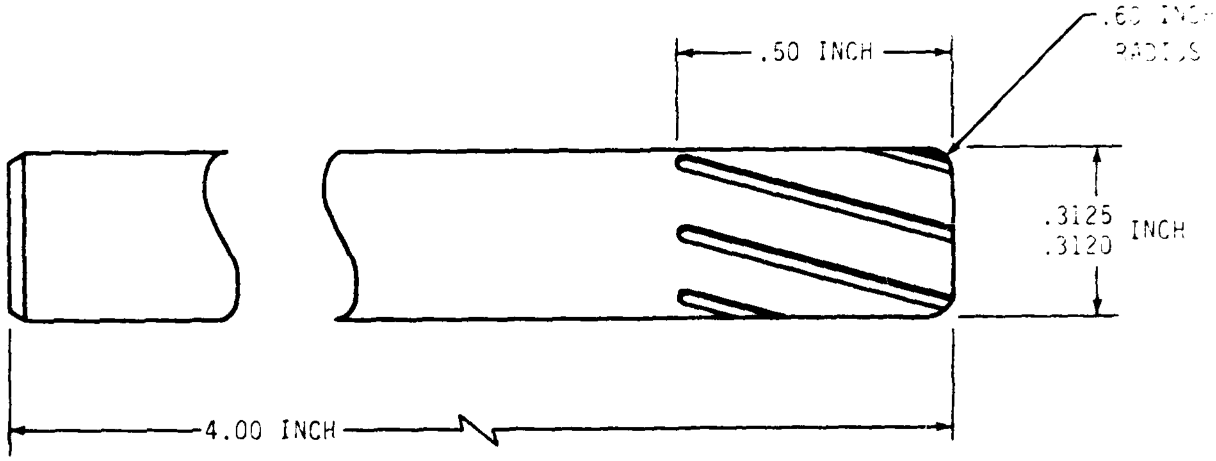



Figure 53. Typical Blisk Airfoil Rough Contour Milling Cutter Requirements.

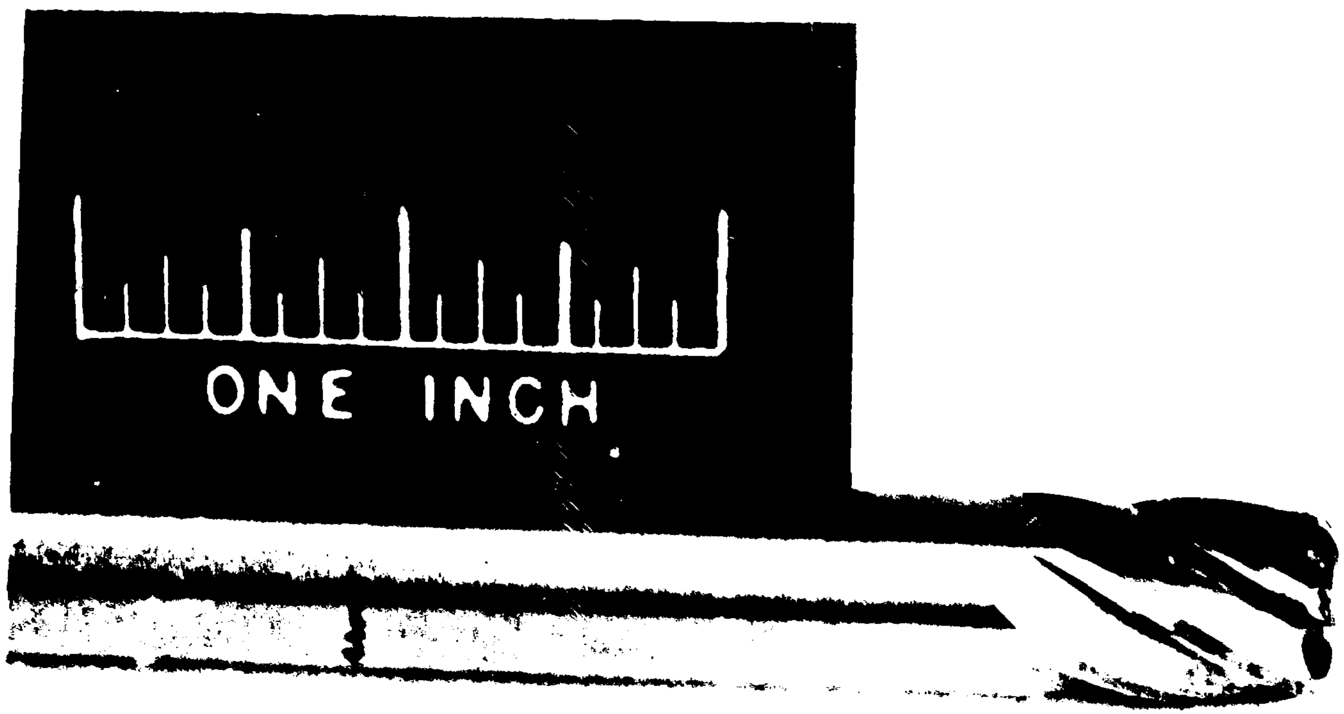



Figure 54. Typical Rough Contour Milling Cutter.

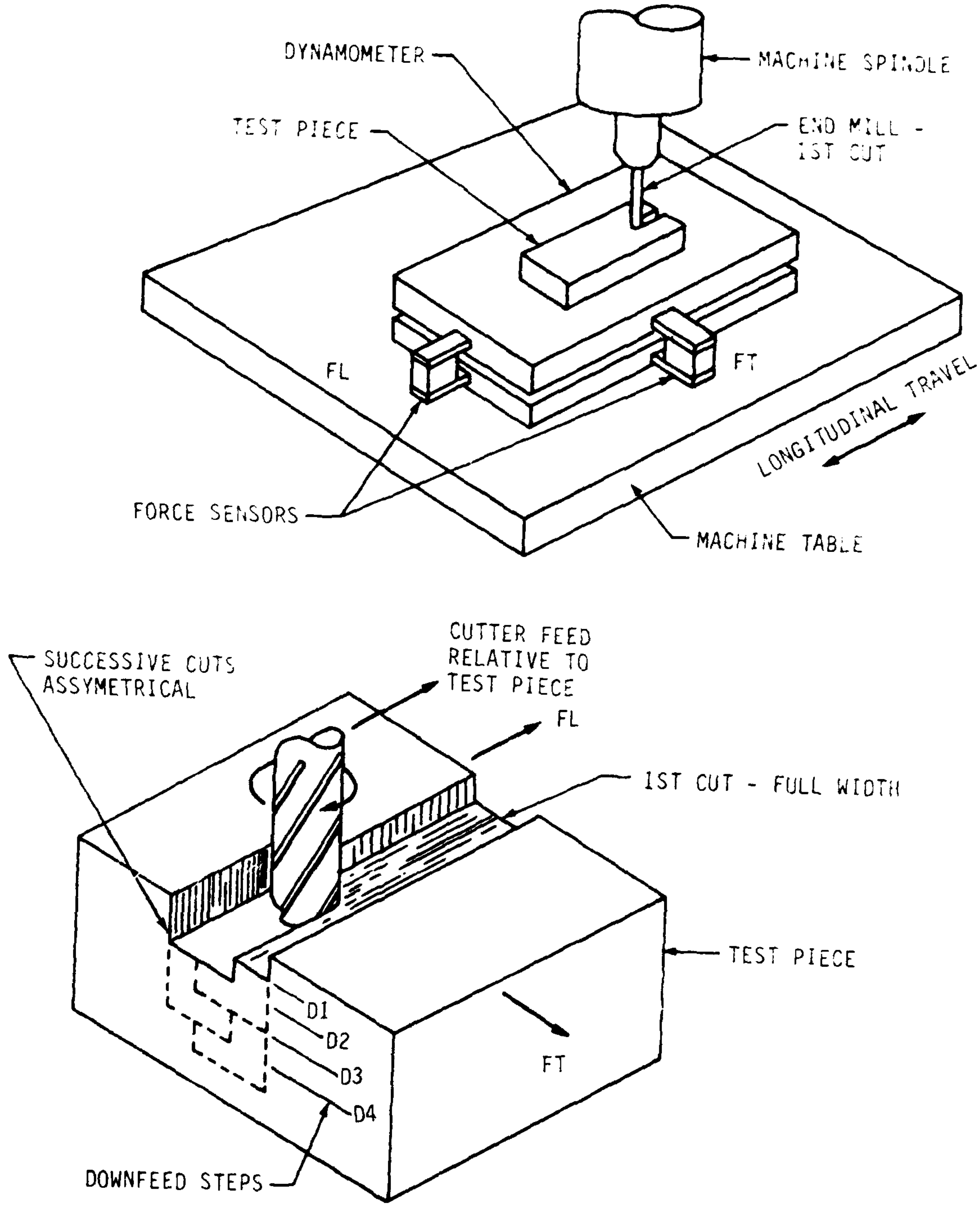
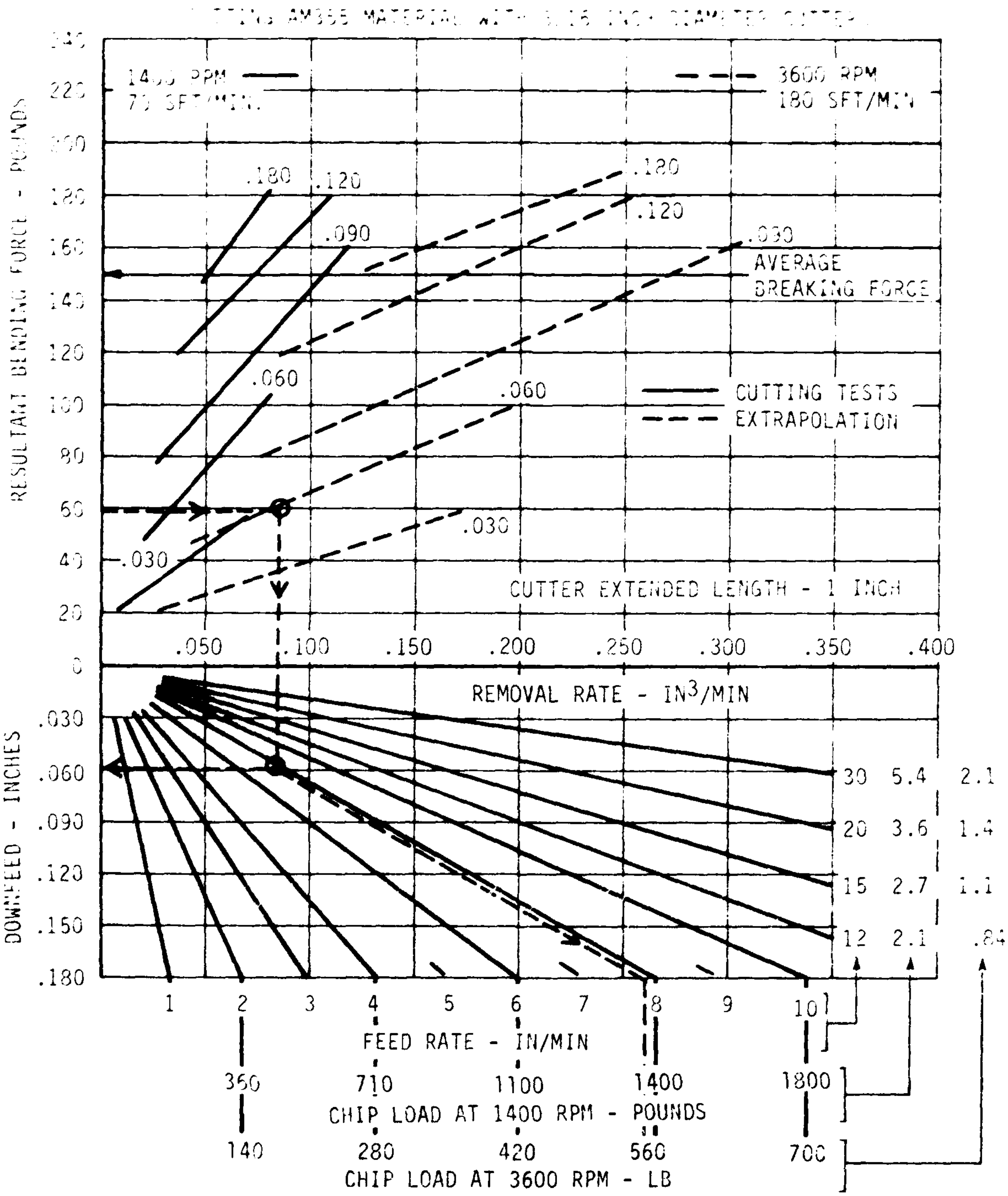
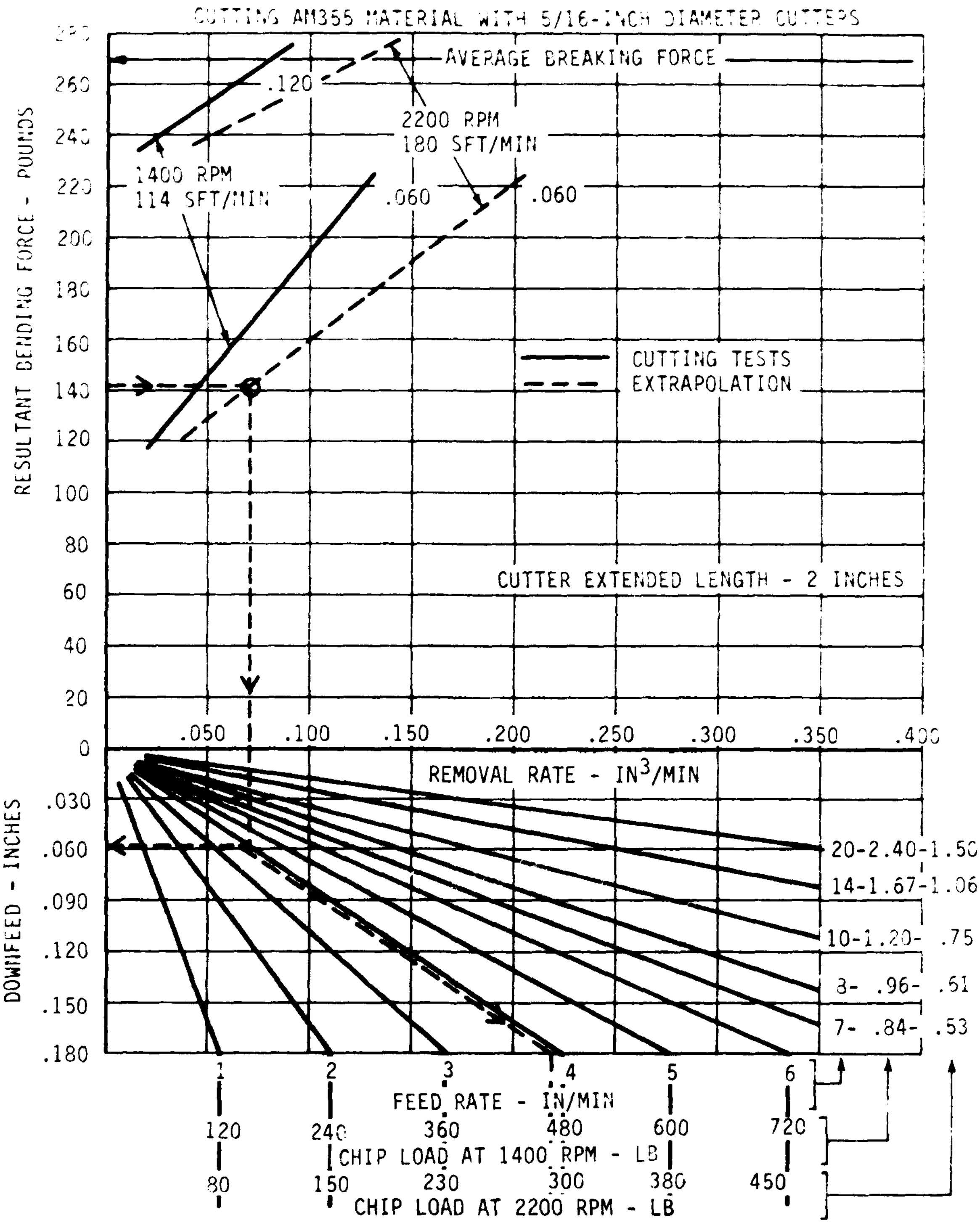



Figure 55. Rough Contour Milling Cutter Force Test Arrangement




CUTTER DESCRIPTION: .1875-inch diameter, 4 flutes, 30-degree helix, 0-degree rake, 6-degree relief, .060-inch corner radius, 883 carboloy.
CUTTING FLUID: Thrall No. 516, Sulfochlorinated Oil

Figure 56. Rough Contour Milling Cutter Force.




CUTTER DESCRIPTION: .312-inch, diameter, 6 flutes, 30-degree helix, 0-degree rake 6-degree relief, 060-inch corner radius, 883 carboloy.
CUTTING FLUID: Thrall No. 516, Sulfochlorinated oil.

Figure 57. Rough Contour Milling Cutter Force.

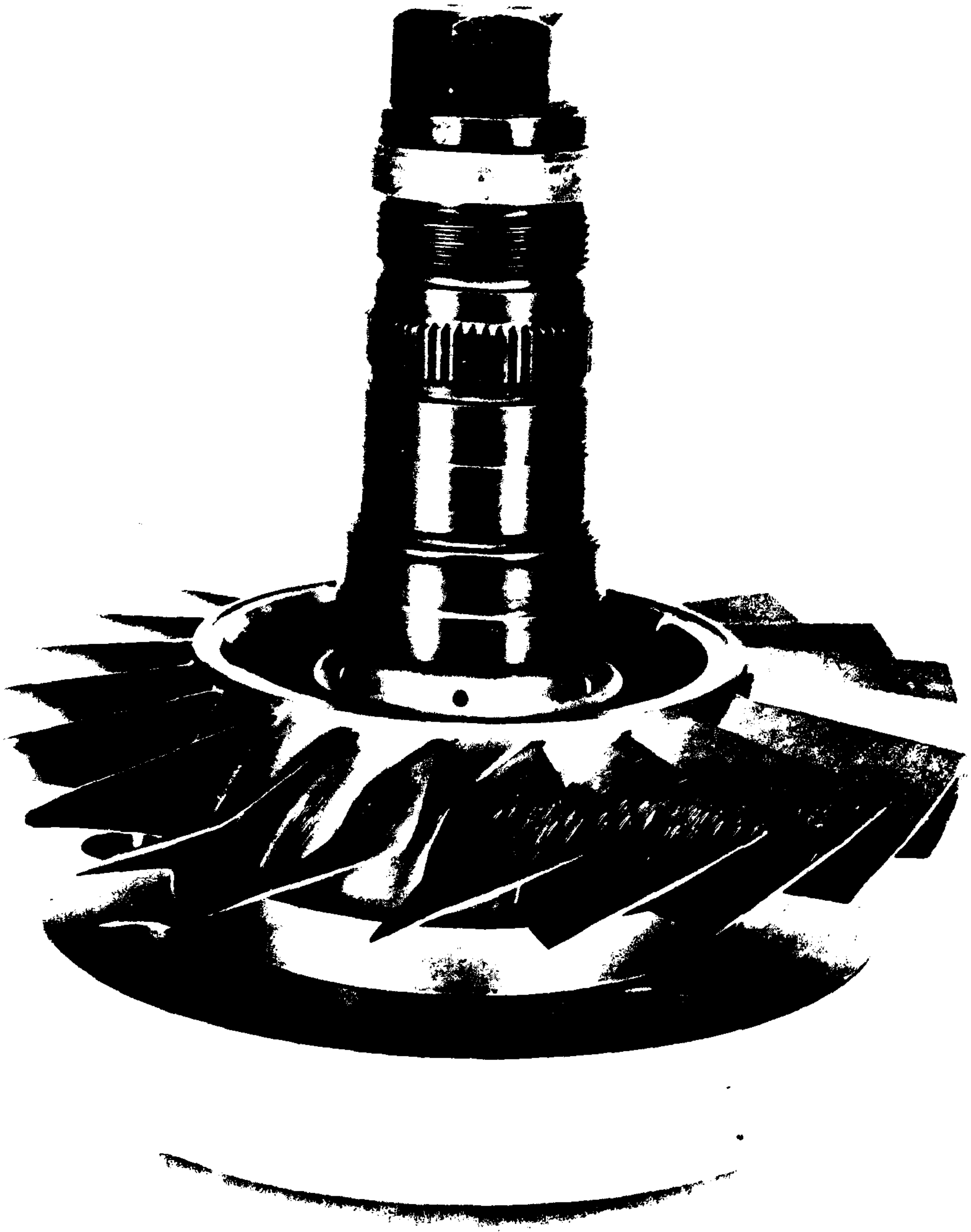


Figure 58. Airfoil NC Contour Milling Fixture Holding Stage I Blisk.

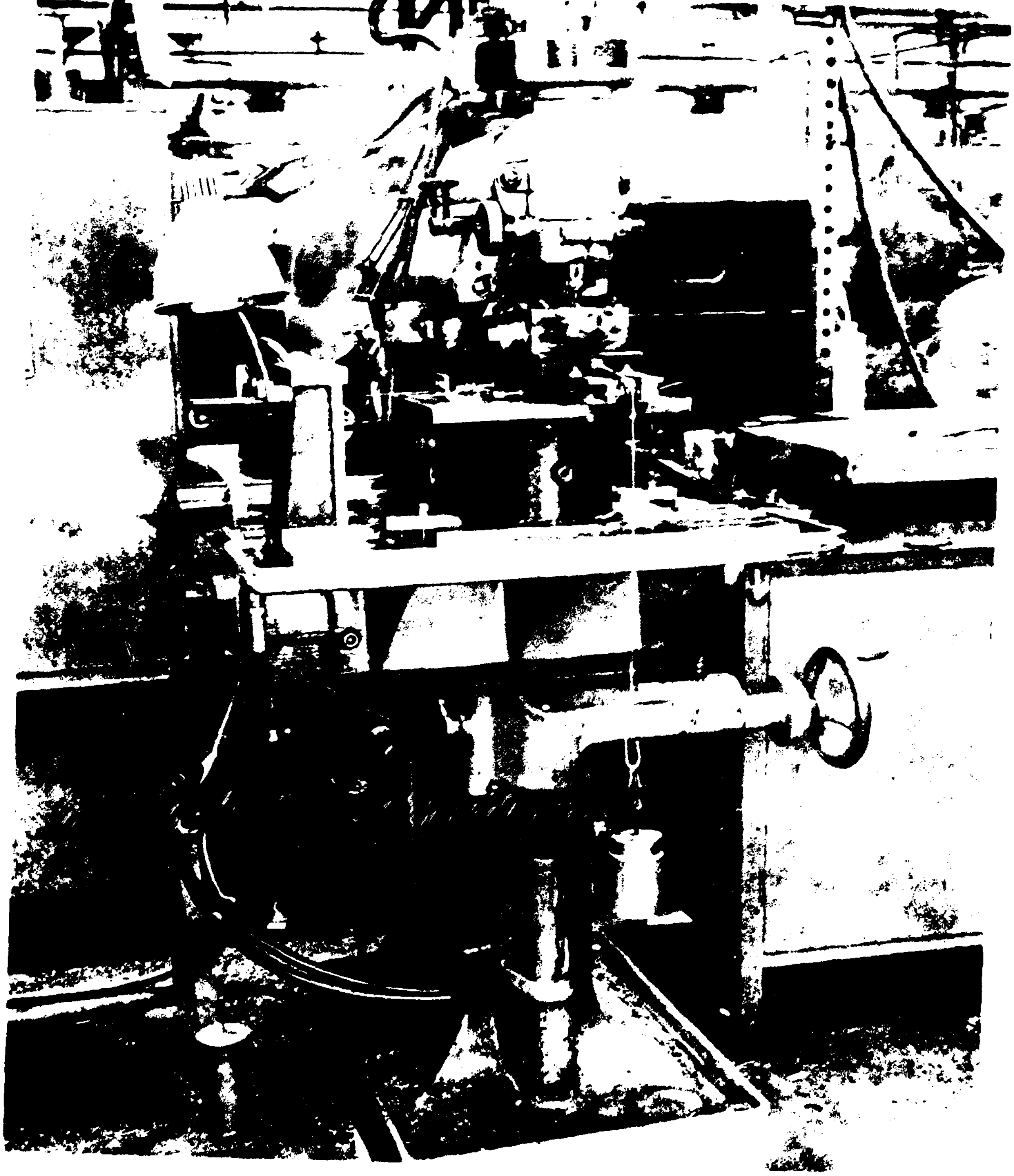
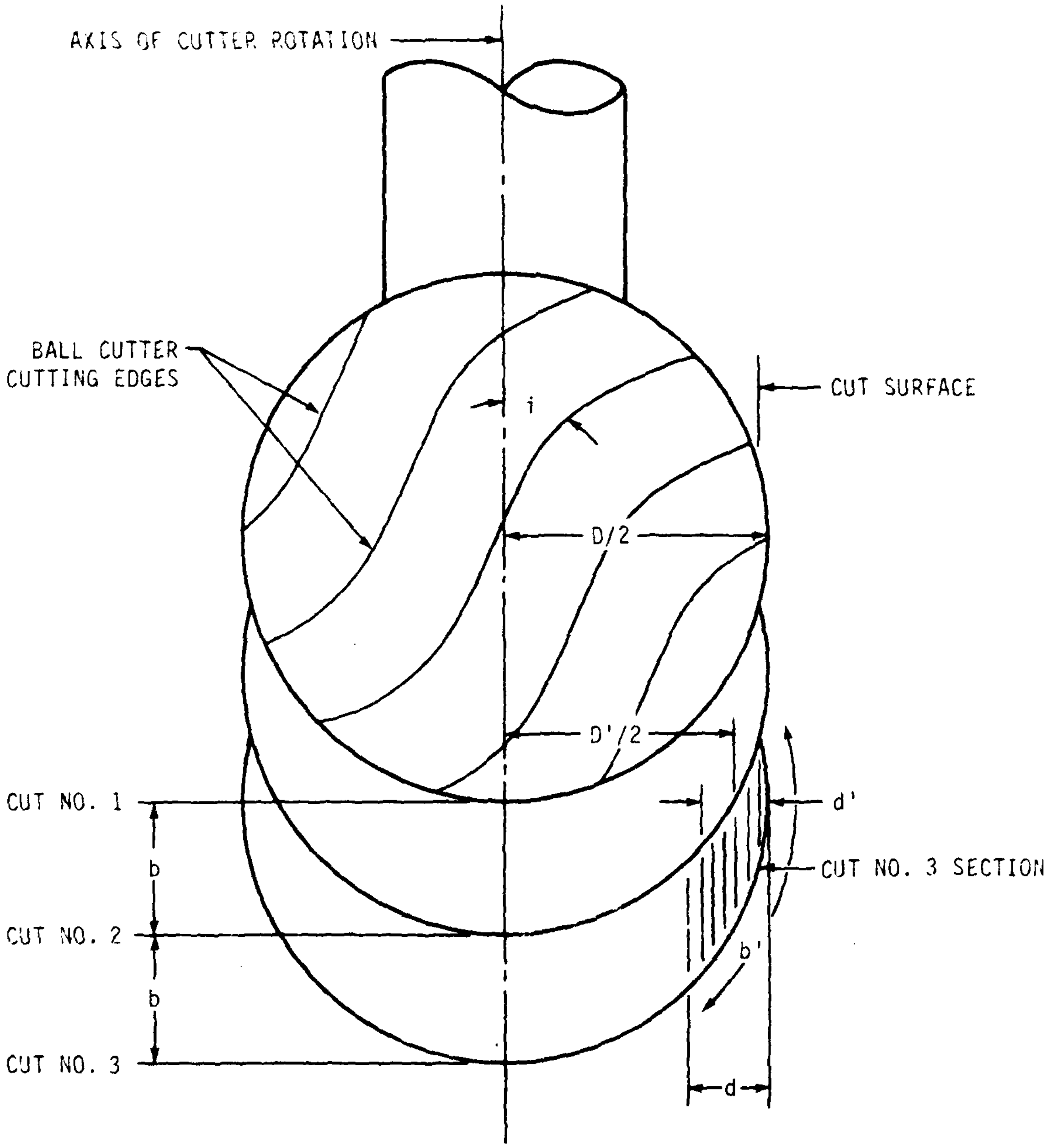
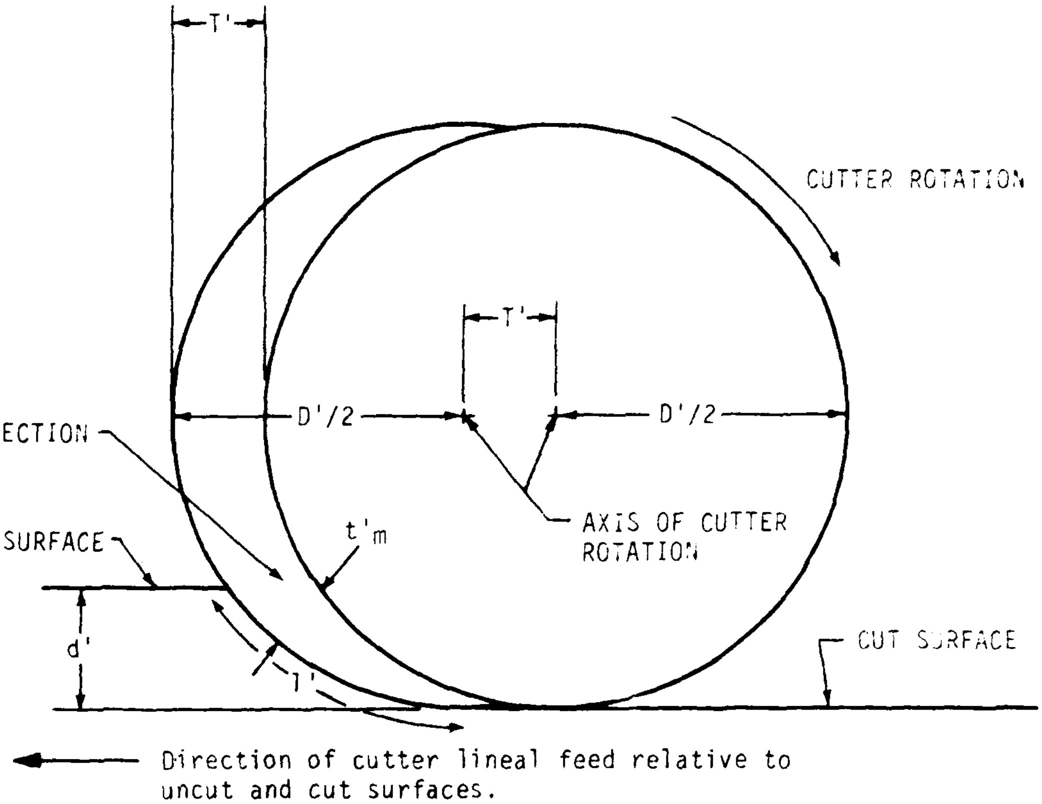


Figure 59. Dynamometer Setup on Deckel Miller.




i = Cutting edge inclination angle.
d = Set depth of cut.
b = Set width of cut (downfeed).
d' = Average depth of cut for actual cut geometry.
b' = Average width of cut for actual cut geometry.
D/2 = Average cutting radius.

Figure 60. Cutter and Cut Geometry.



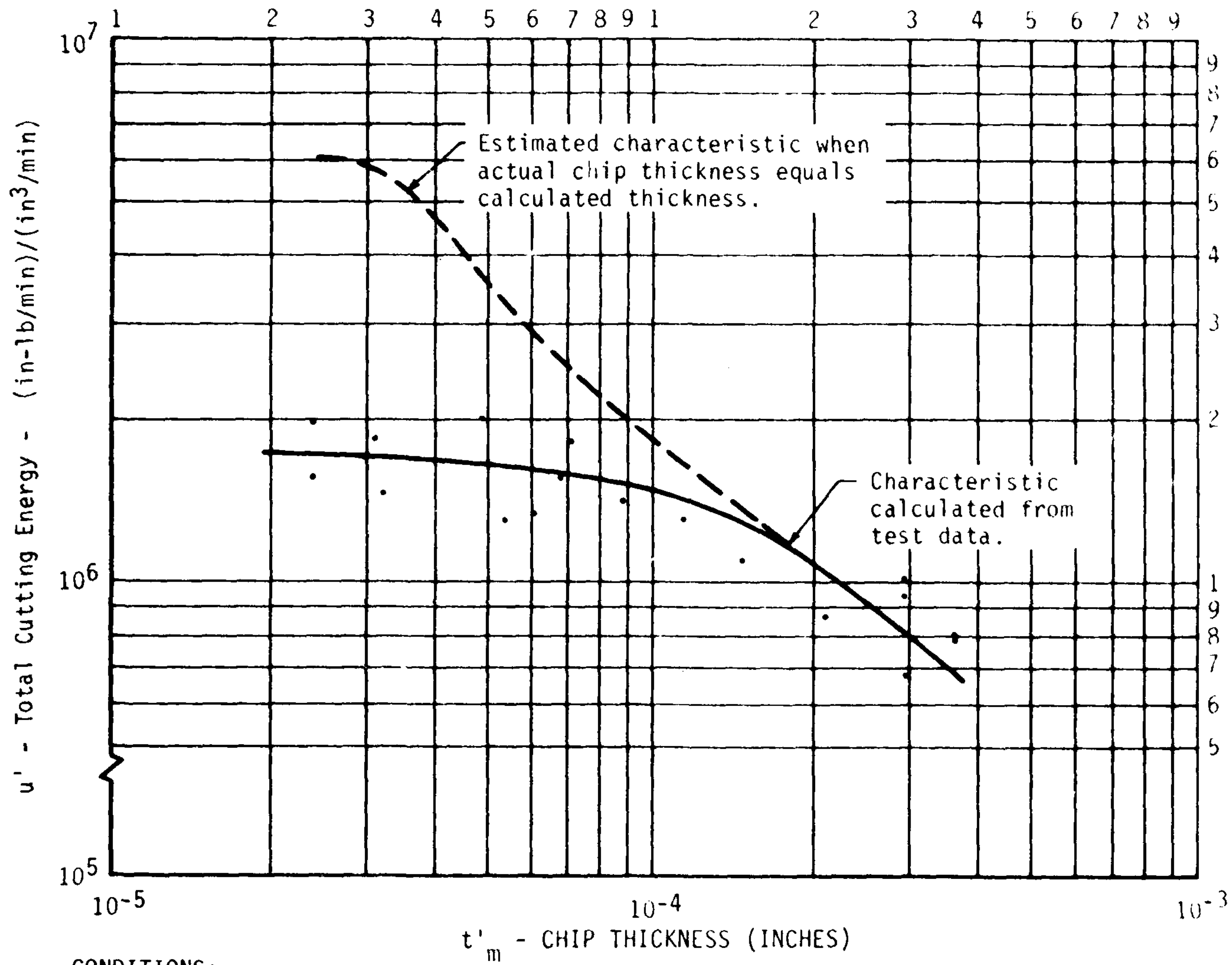

Cutter and cut are shown in section through plane D'/2 in Figure 62 perpendicular to cutter axis.

T' = Chip load (feed per tooth).

$t'_m$ = Maximum chip thickness at average diameter of actual cut geometry (undeformed thickness).

l' = Undeformed chip length at average diameter of actual cut.

Figure 61. Cutter and Cut Geometry.




CONDITIONS:

Cutter Diameter = 3/8 inch, 32 Tooth Carbide Ball Speed = 1,900 to 6,000 rpm,
Lineal Feed = 7.5 to 97 in/min.

$\alpha$ = not determined, Tangential Force = 1.7 to 10.5 pounds, Set Depth = 20 to 50 mils.

i = 20 degrees, cos i = .94 (neglected).

Figure 62. Cutting Energy Related to Chip Thickness.

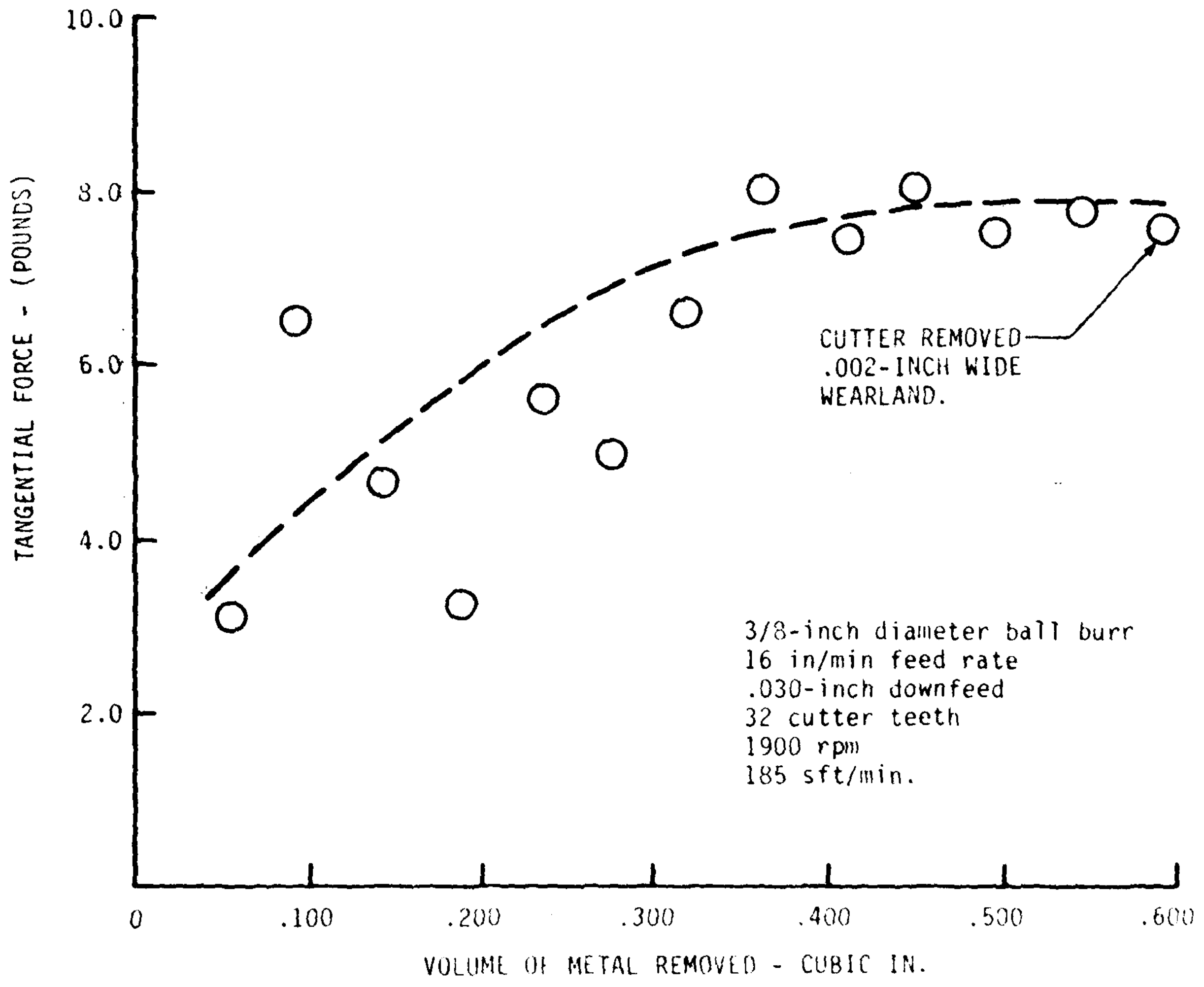



Figure [illegible]. Wear Test of Tungsten Carbide Cutter on [illegible] Material.

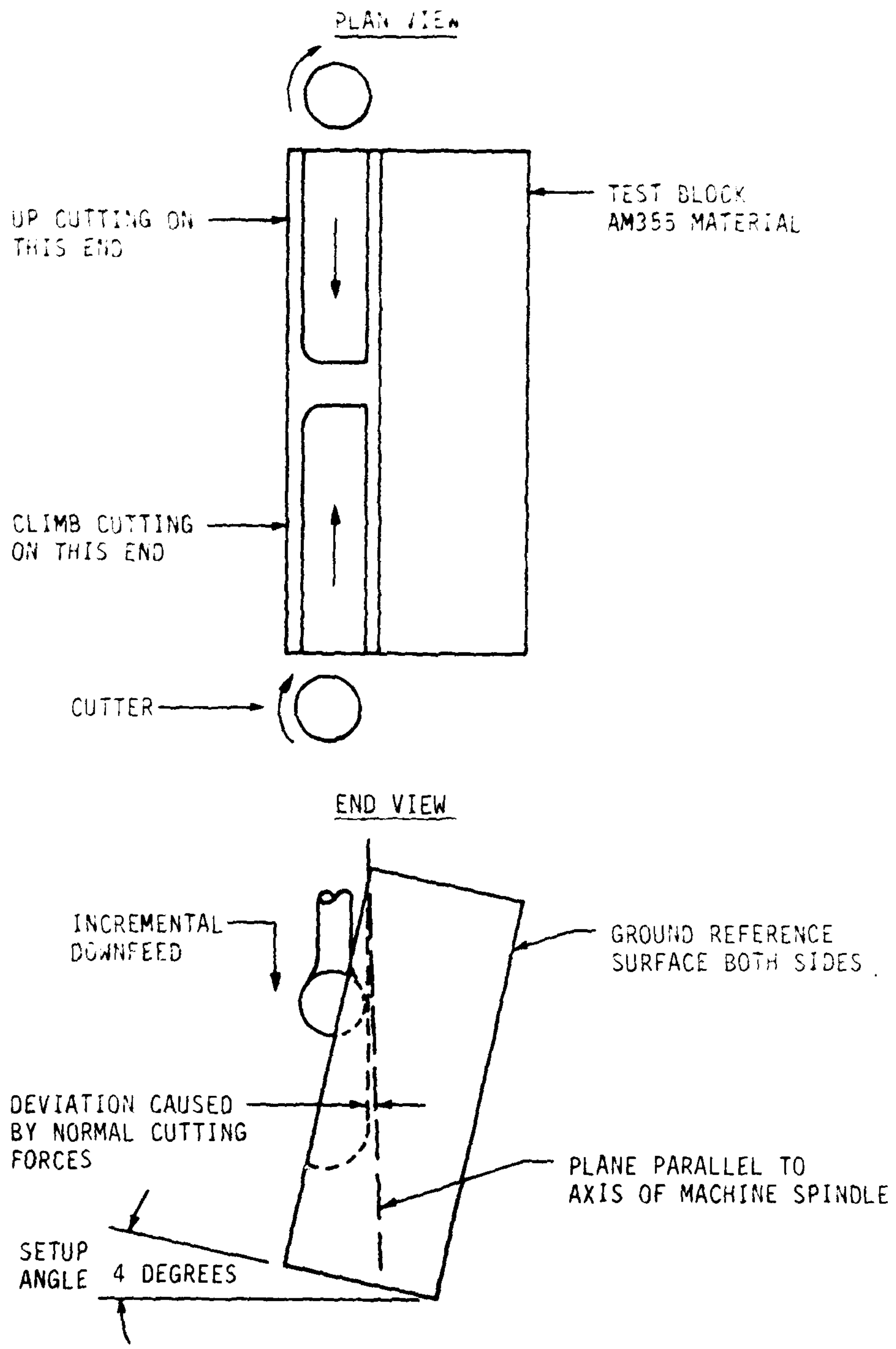



Figure 64. Test Method and Test Block Setup for Determination of Normal Cutting Forces.

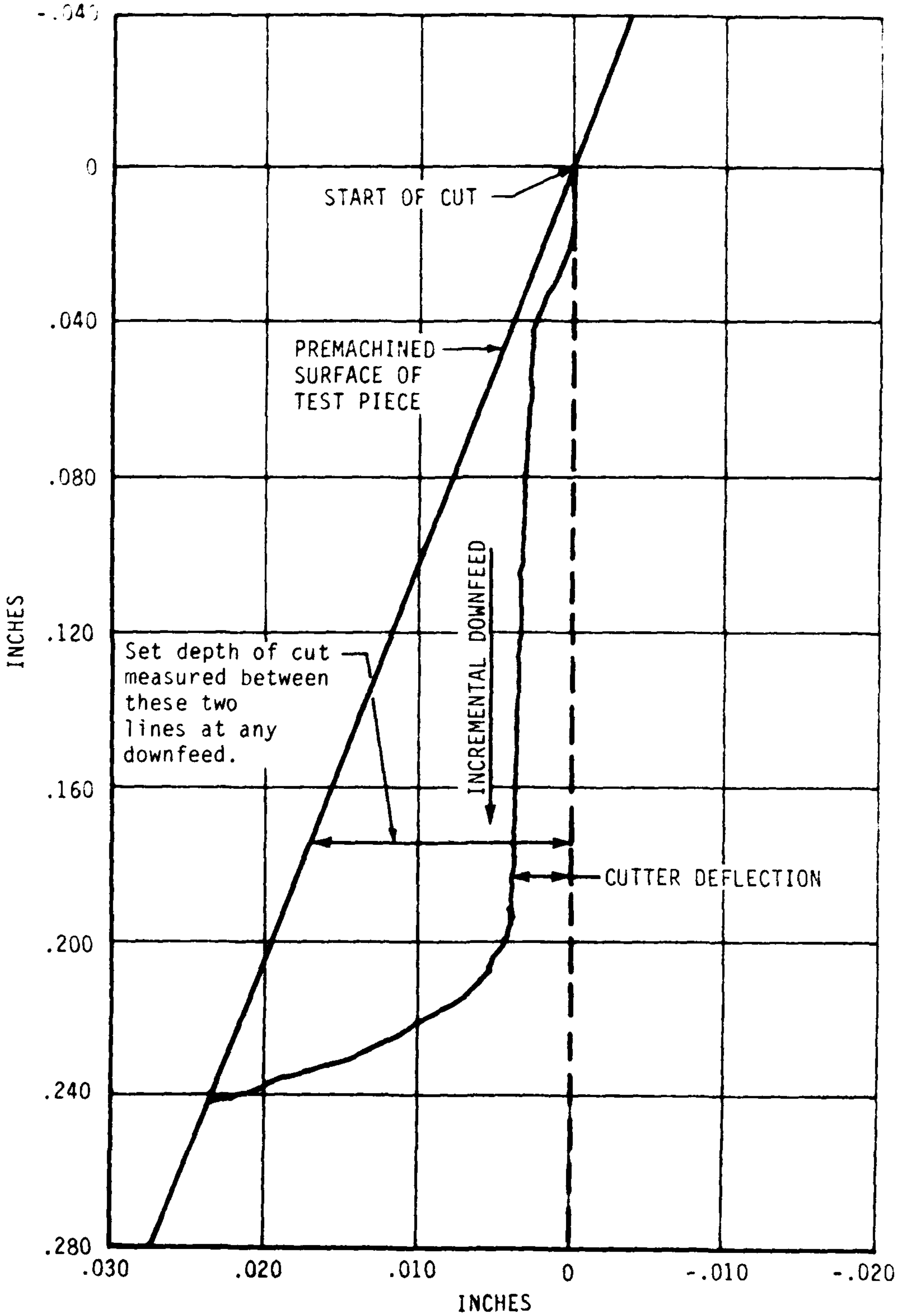



Figure 65. Contoureader Trace of Machined Surface Deviation Caused by Normal Cutting Force.

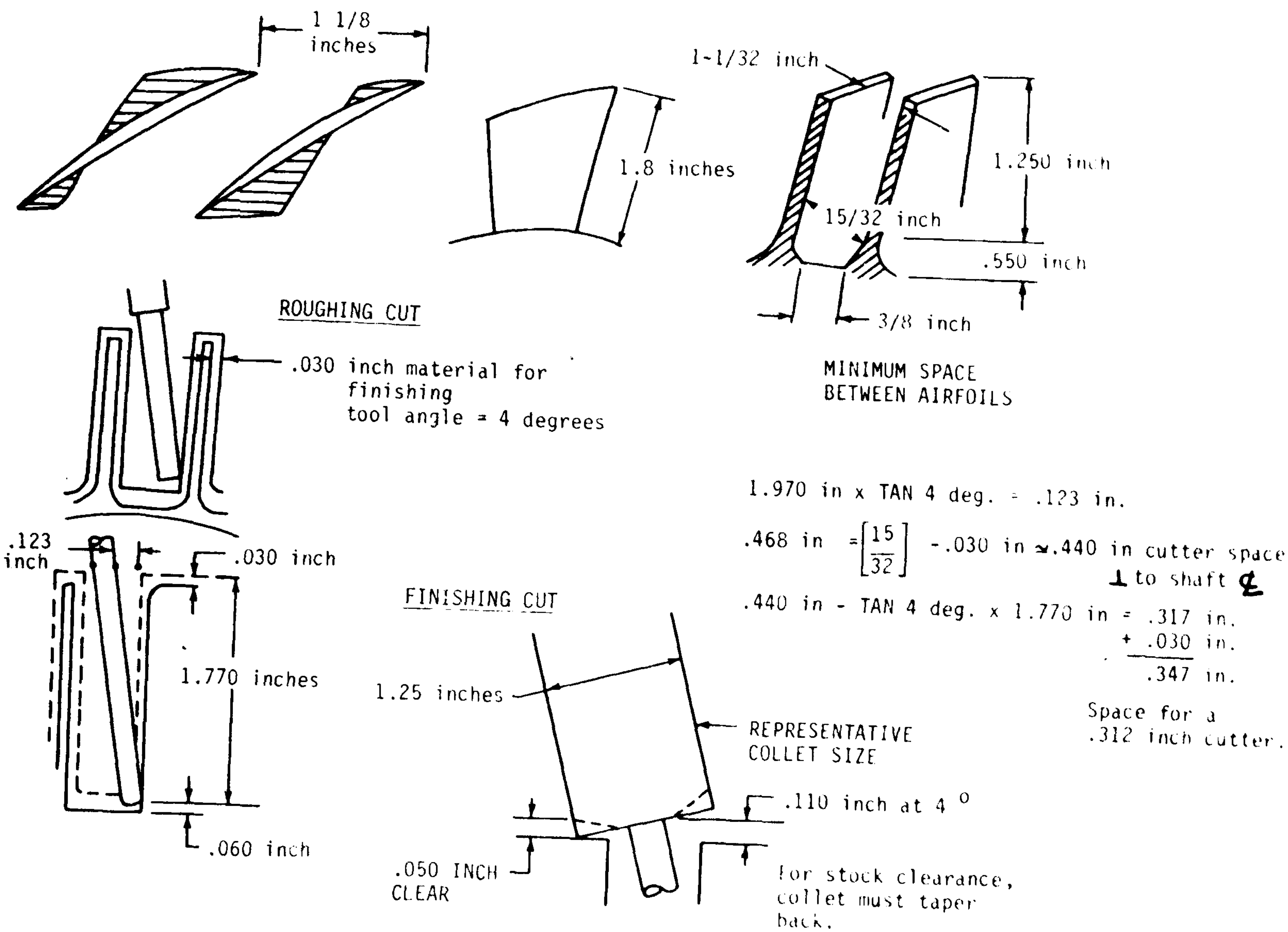



Figure 66. Typical Analysis of Tool Diameter and Length for Contour Milling.

CARBIDE GRADE - 883

| | |
|---|---|
| Number of Flutes: | 12 |
| Flute Helix: | 30 degrees right hand spiral |
| Flute-to-Flute Variance: | .0005 inch max |
| Cylindrical Margin on OD and Radius: | .002 - .003 inch |
| Rake Angle: | 30 ±3 degrees negative |
| Relief Angle: | Standard 45 degrees |

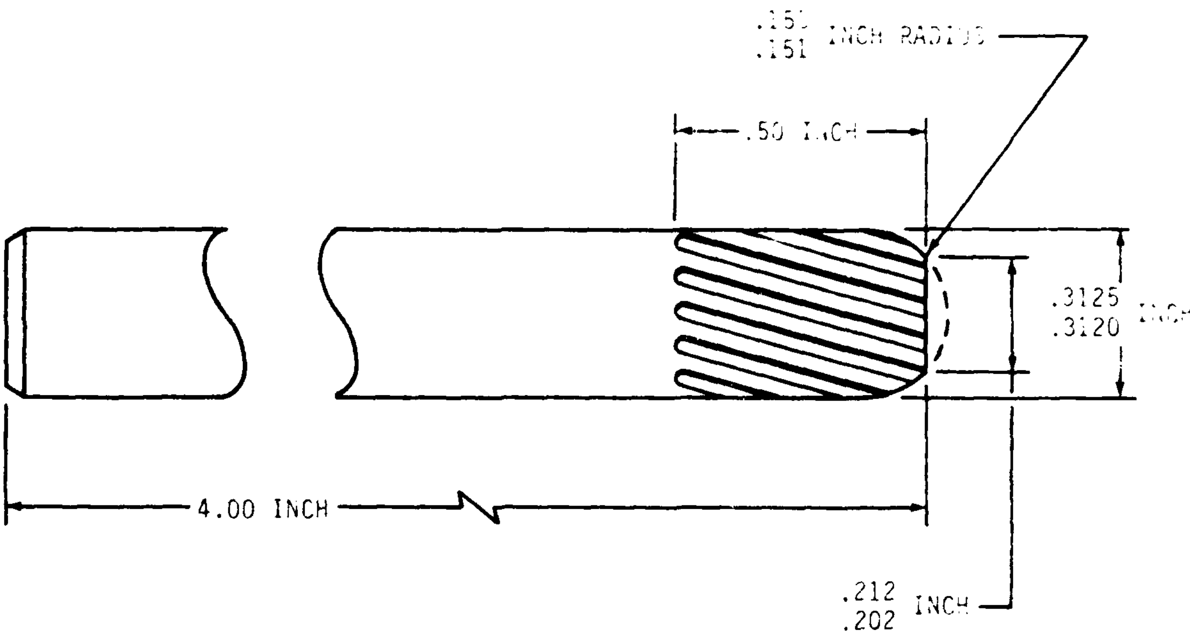



Figure 67. Typical Blisk Airfoil Finish Contour Milling Cutter Requirements.

CARBIDE GRADE - 883

| | |
|---|---|
| Number of Flutes: | 16 |
| Flute Helix: | 30 degrees right hand spiral |
| Flute-to-Flute Variance: | .0005 inch max |
| Cylindrical Margin on OD and Radius: | .002 - .003 inch |
| Rake Angle: | 30 $\pm$3 degrees negative |
| Relief Angle; | Standard 45 degrees |

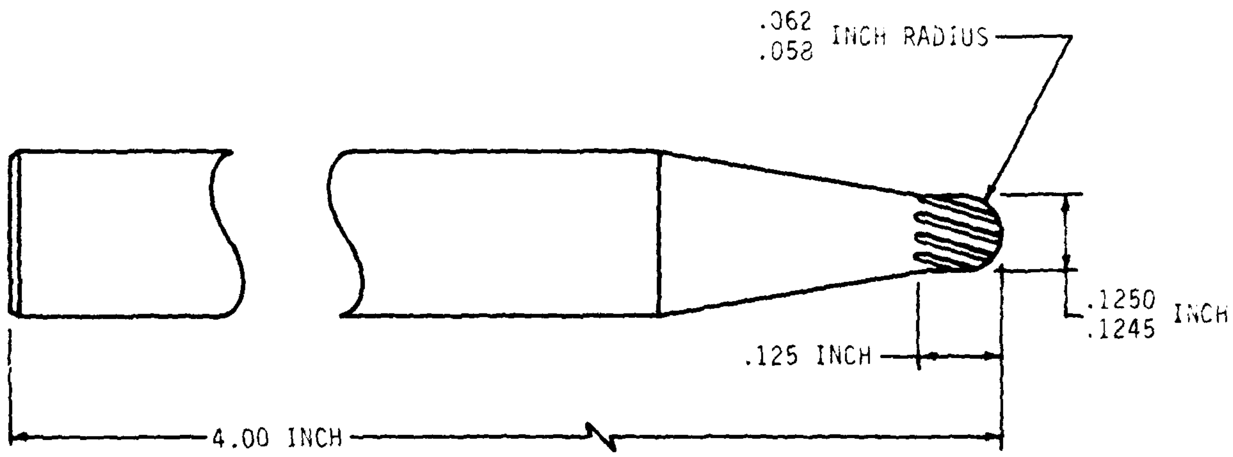



Figure 68. Typical Blisk Platform Finish Milling Cutter Requirements.

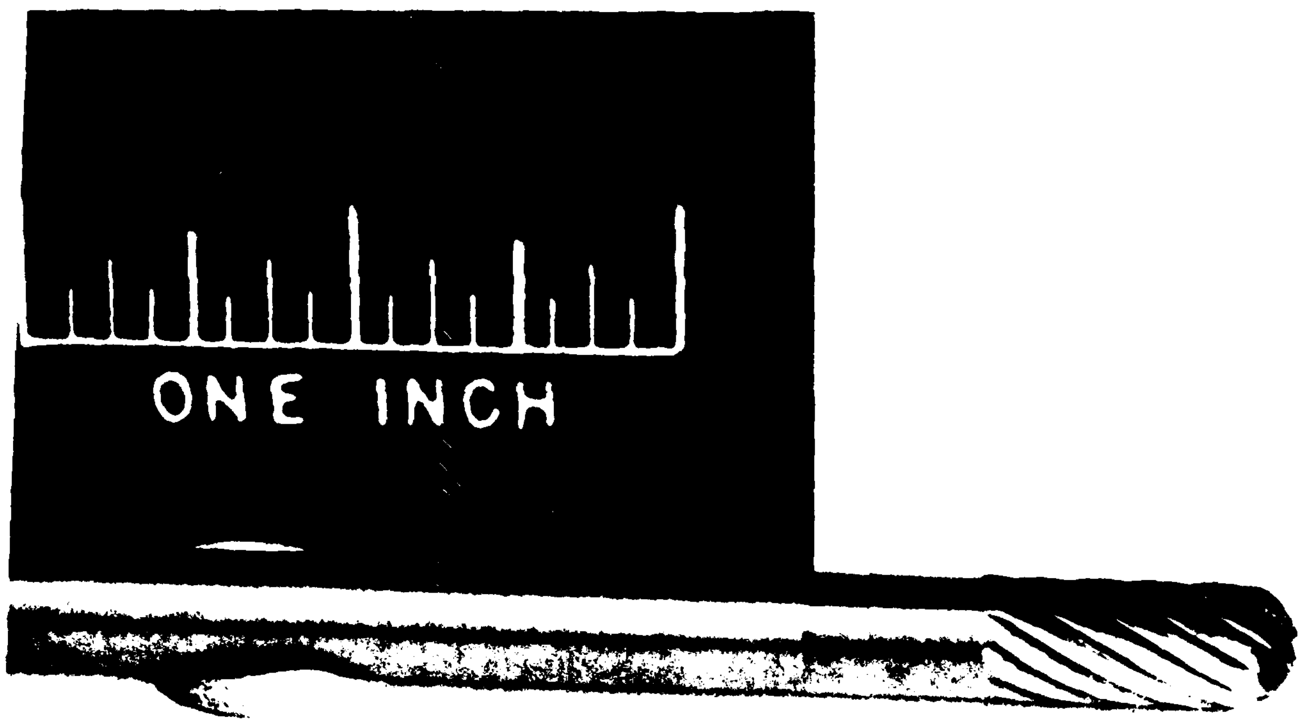



Figure 69. Typical Airfoil Finish Contour-Milling [illegible].

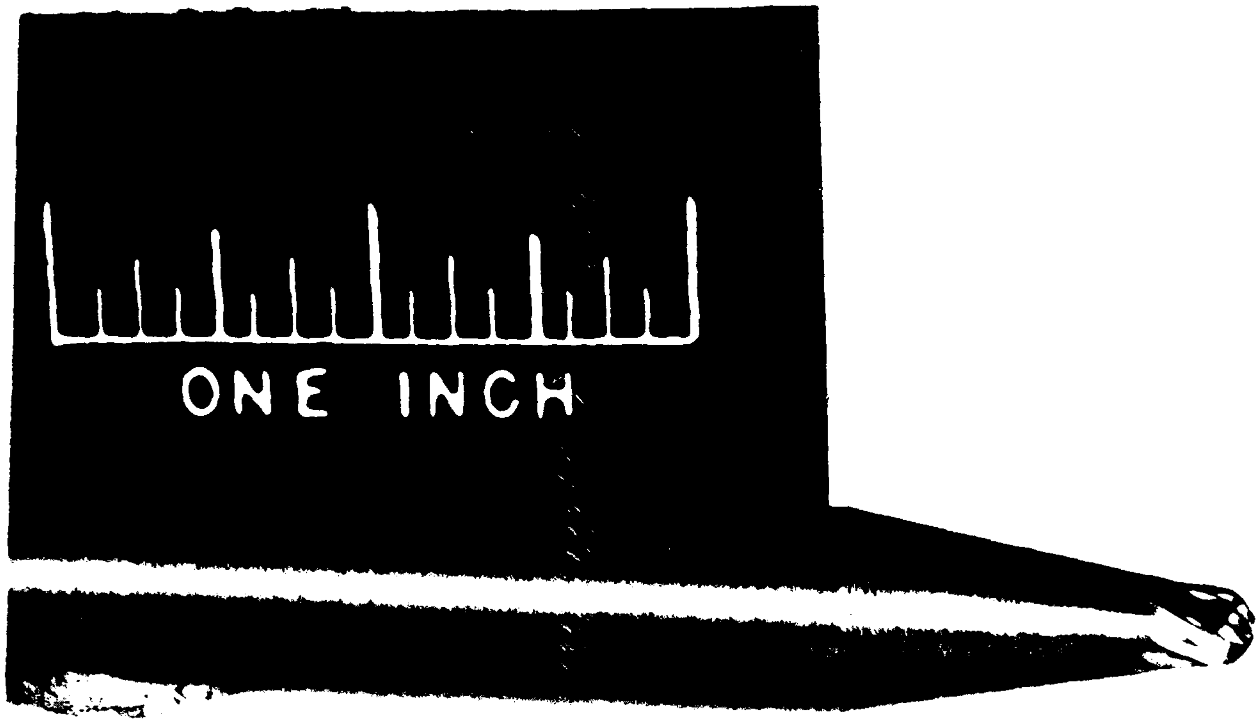



Figure 70. Typical Platform and Fillet Finish Contour-Milling Cutter.

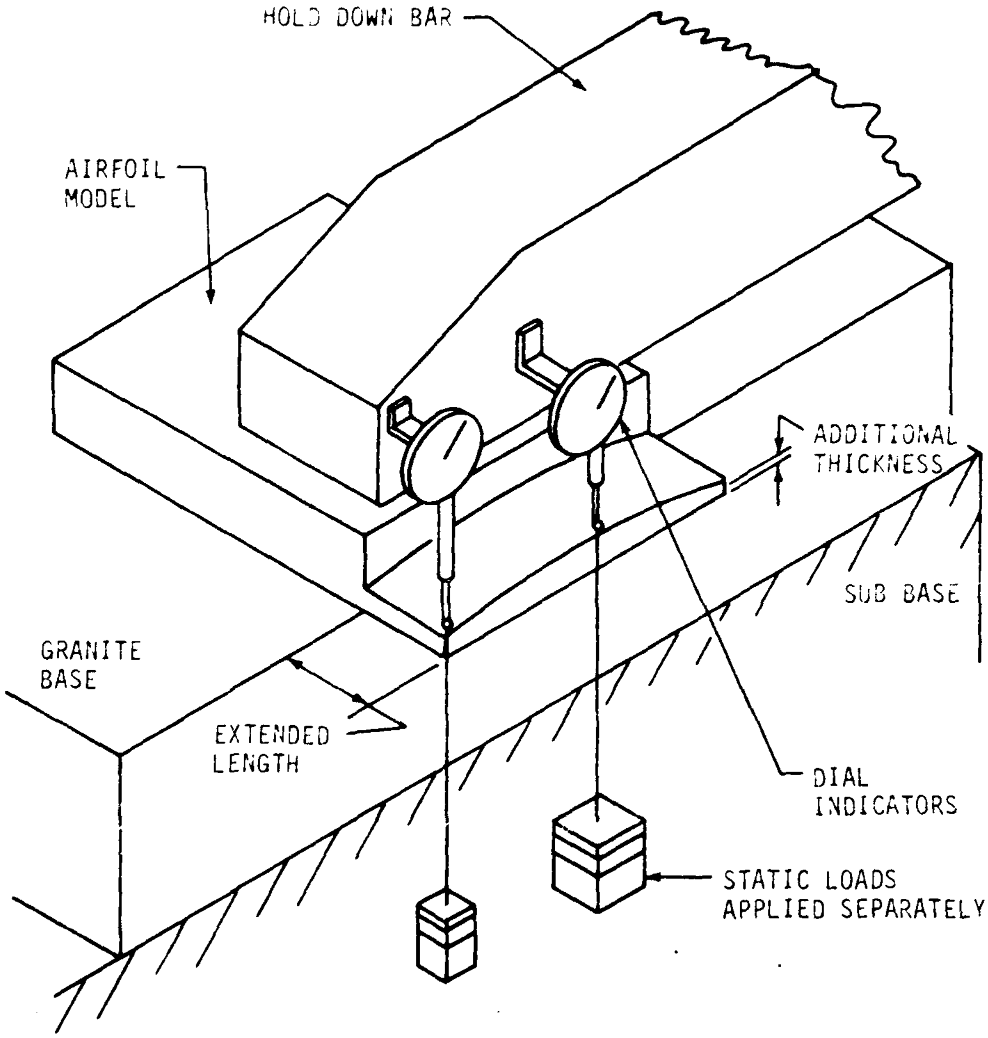
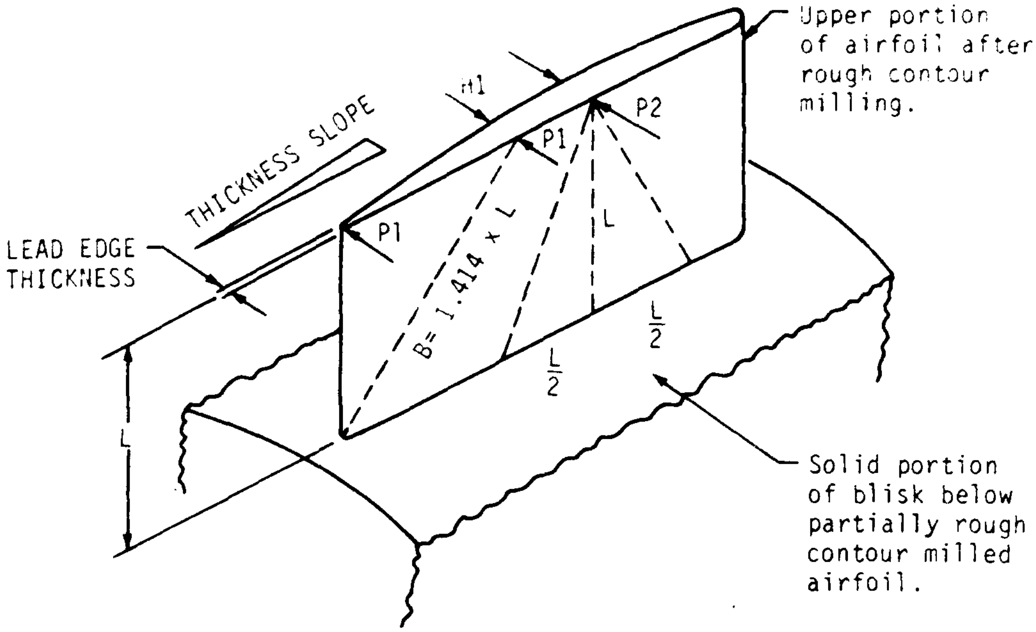



Figure 71. Test Setup for Static Deflection Tests on Modeled Airfoil.




$\Delta$ = Static deflection at lead edge corner - inches. $= 7P_1L^3/B(H/2)^3E$ (1)

$\Delta$ = Static deflection at or near the stacking axis - inches. $= 7P_2L^2/H^3E$ (2)

$P_1$ = Force applied normal to the neutral axis at the lead edge corner - pounds.

$P_2$ = Force applied normal to the neutral axis at the tip of the extended length - pounds.

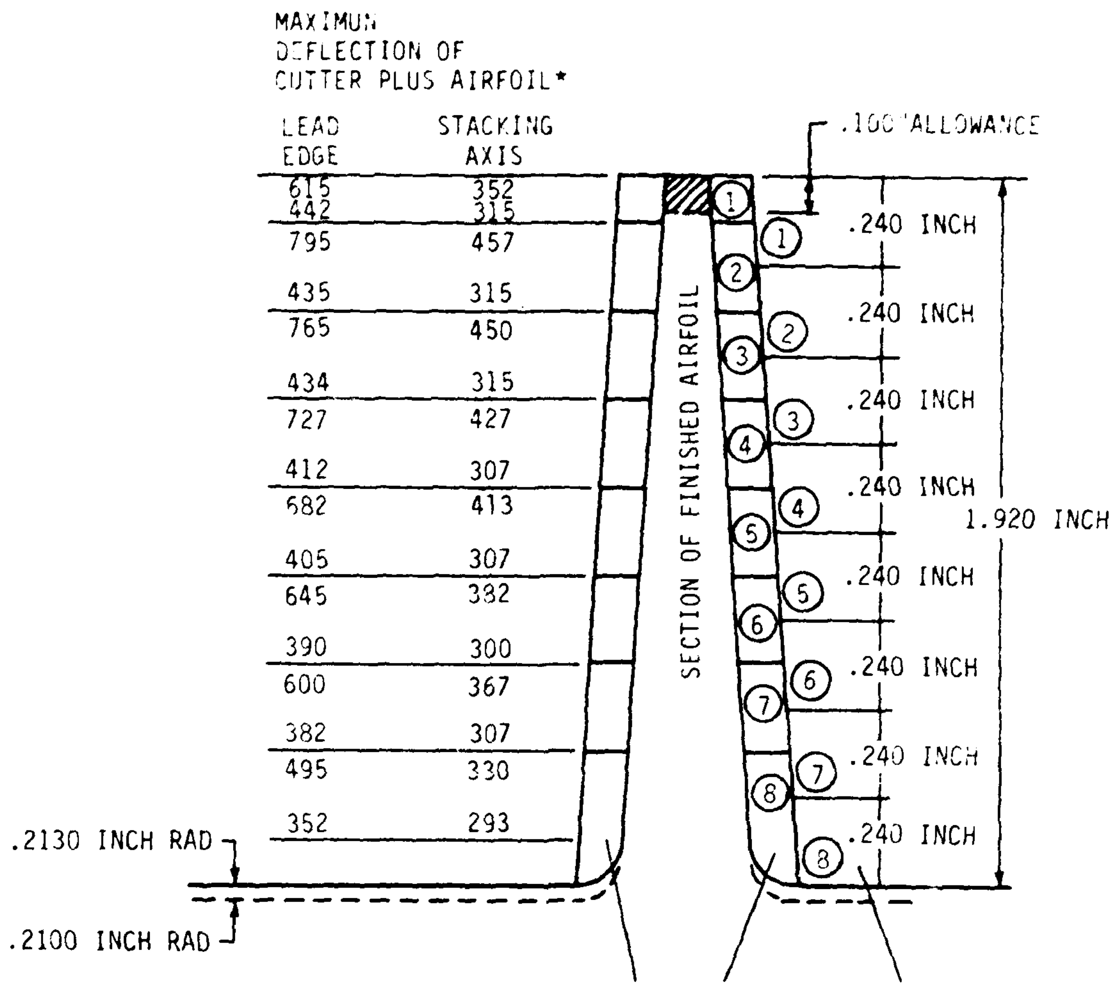
L = Extended length - inches.

E = Modulus of elasticity (Young E) - $30.0 \times 10^6$ pound/in.$^2$

$H_1$ and $H_2$ = Computed thickness based on lead edge thickness and approximate slope toward the stacking - inches.

B = Computed corner diagonal distance determined by the extended length - inches.

Figure 72. Equations for Estimating Deflection of Blisk Airfoils Under Finish Contour Milling Conditions.




*Numbers between lines delineating each finishing increment are maximum deflection (upper number) and minimum deflection (lower number)-microinches.

Material removed by finish cutter milling in increments following each roughing increment having the same number.

Material removed by rough cutter milling in increments enclosed by circled numbers.

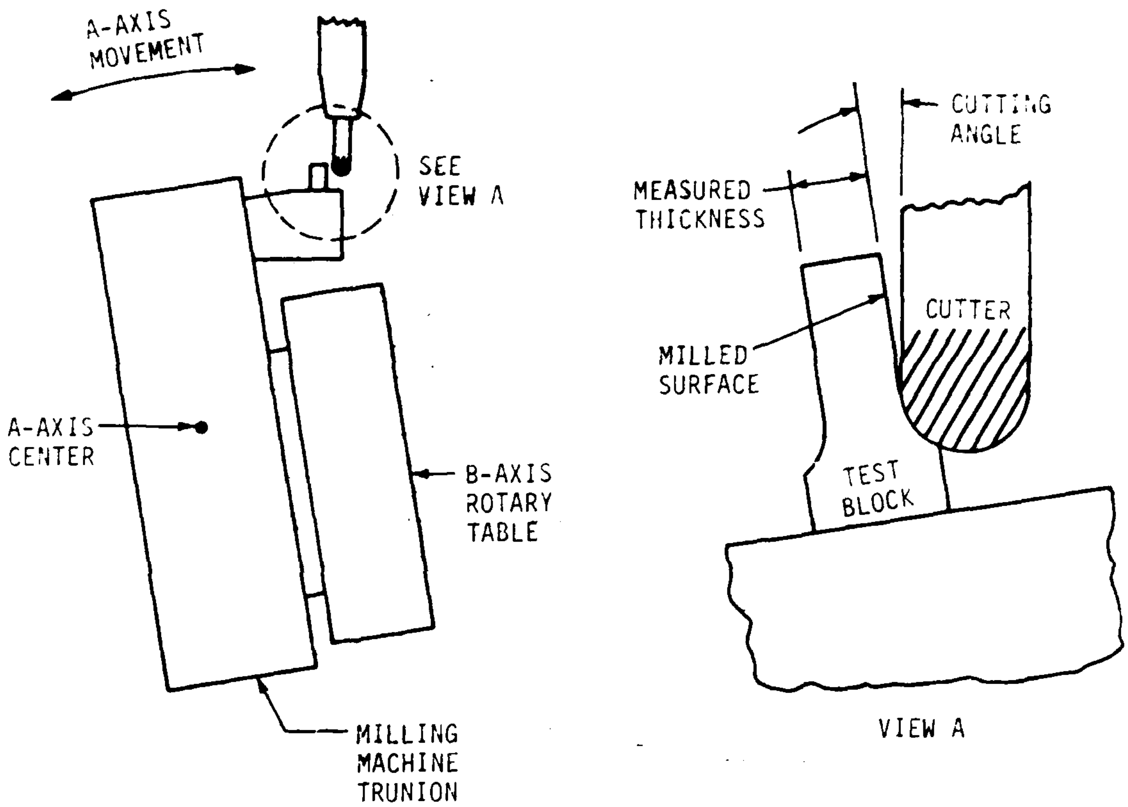
Finish Contour Milling Parameters

10,000 rpm/815 sft/min
30 inches/min feed rate
.030 inch depth of cut
.015 inch downfeed
estimated normal force=7.5 lb

Finish Contour Milling Cutter

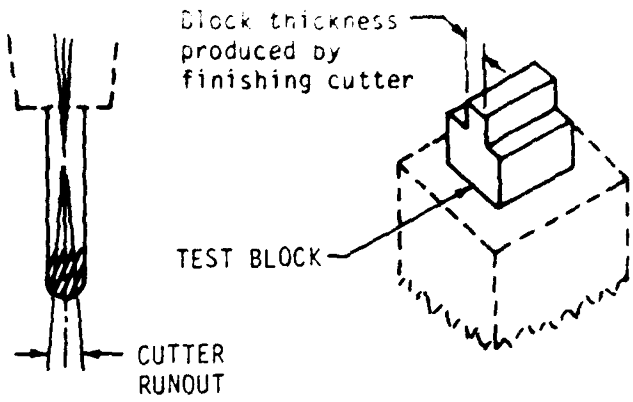
5/16-inch dia carbide truncated ball end
5/16-inch dia carbide shank
1.725 inch extended shank length
30 teeth

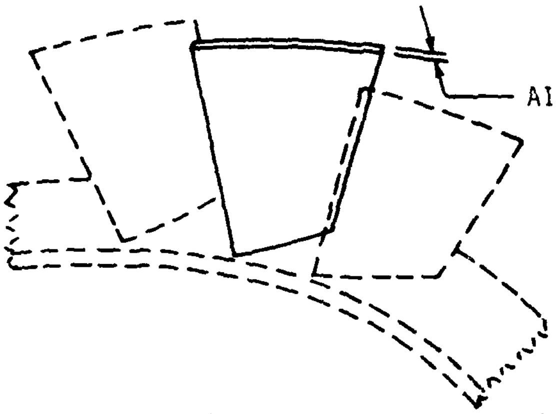
Figure 73. Incremental Rough and Finish Contour Milling Deflection Estimates for Blisk Stage 1 Airfoil.




Right side of test block milled with trunion rotated counter-clockwise to produce cutting angle shown. Left side milled with trunion rotated clockwise to produce some cutting angle.

Figure 74. Test Block Setup.




BLISK: STAGE 1 SERIAL NO. 78144
SECTIONS DD, FF, HH.

| | As Milled | After Abrasive Flow Machine |
|---|---|---|
| SAMPLE (number of measurements) | 136 | 161 |
| Airfoil Mean (mils) | 1.95 | 1.00 |
| Standard Deviation - Airfoils (mils) | 1.68 | 1.45 |
| Block Mean (mils) | 1.65 | 1.76 |
| Standard Deviation - Block (mils) | 0.83 | 0.75 |
| Runout Mean (mils) | | 0.80 |
| Standard Deviation - Runout (mils) | | 0.26 |
| R-Square Block* | 0.3765 | 0.3491 |
| R-Square Runout and Block | | 0.4538 |

*R-Square - Contribution of test block thickness to airfoil thickness as block contributions divided by airfoil thickness variation.

EQUATIONS -

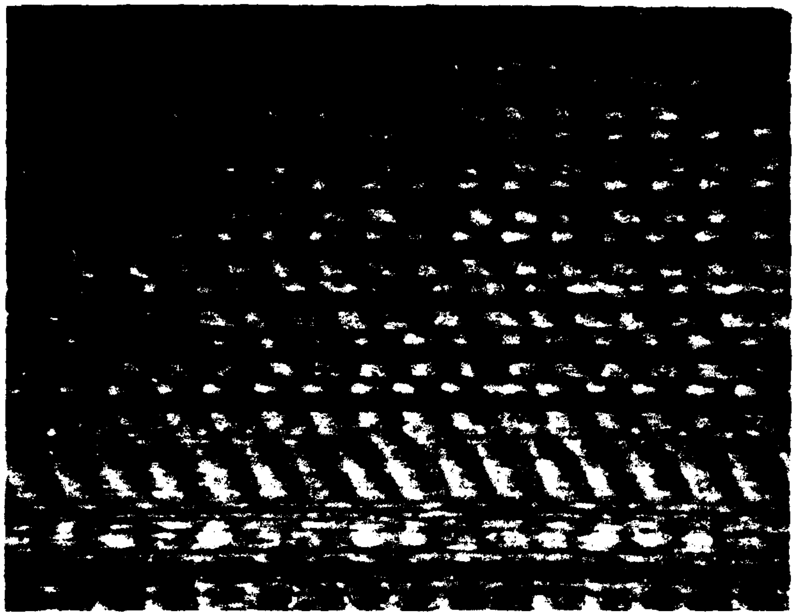
Airfoil Thickness as Milled (in). = -0.106 + 1.24 (block thickness)

Airfoil Thickness After Abrasive Flow Machining (in). = -1.007 + 1.13 (block thickness)

Also

Airfoil Thickness After Abrasive Flow Machining (in). = .505 + 1.09 (block thickness) -1.8 (runout)

Figure 75. Multiple Linear Regression Analysis of Relationship Between Airfoil Thickness, Test Block Thickness, and Airfoil Finish Contour Milling Cutter Runout for Airfoils Milled with Development Machine on Stage 1 Blisk for Engine Testing.



Surface texture (X 30 magnification) side cutting AM355, machined with a stiff system at:

| | |
|---|---|
| Feed Rate----------- | 30 in/min. |
| Depth of Cut-------- | .030 inches |
| Downfeed------------ | .010 inches |
| Cutter Speed-------- | 3,150 rpm |
| Cutter Rate--------- | 307 sft/min. |
| Cutter (Ball) Size-- | 3/8-inch-diameter |
| Teeth--------------- | 20 |

Figure 76. Typical Surface Texture.

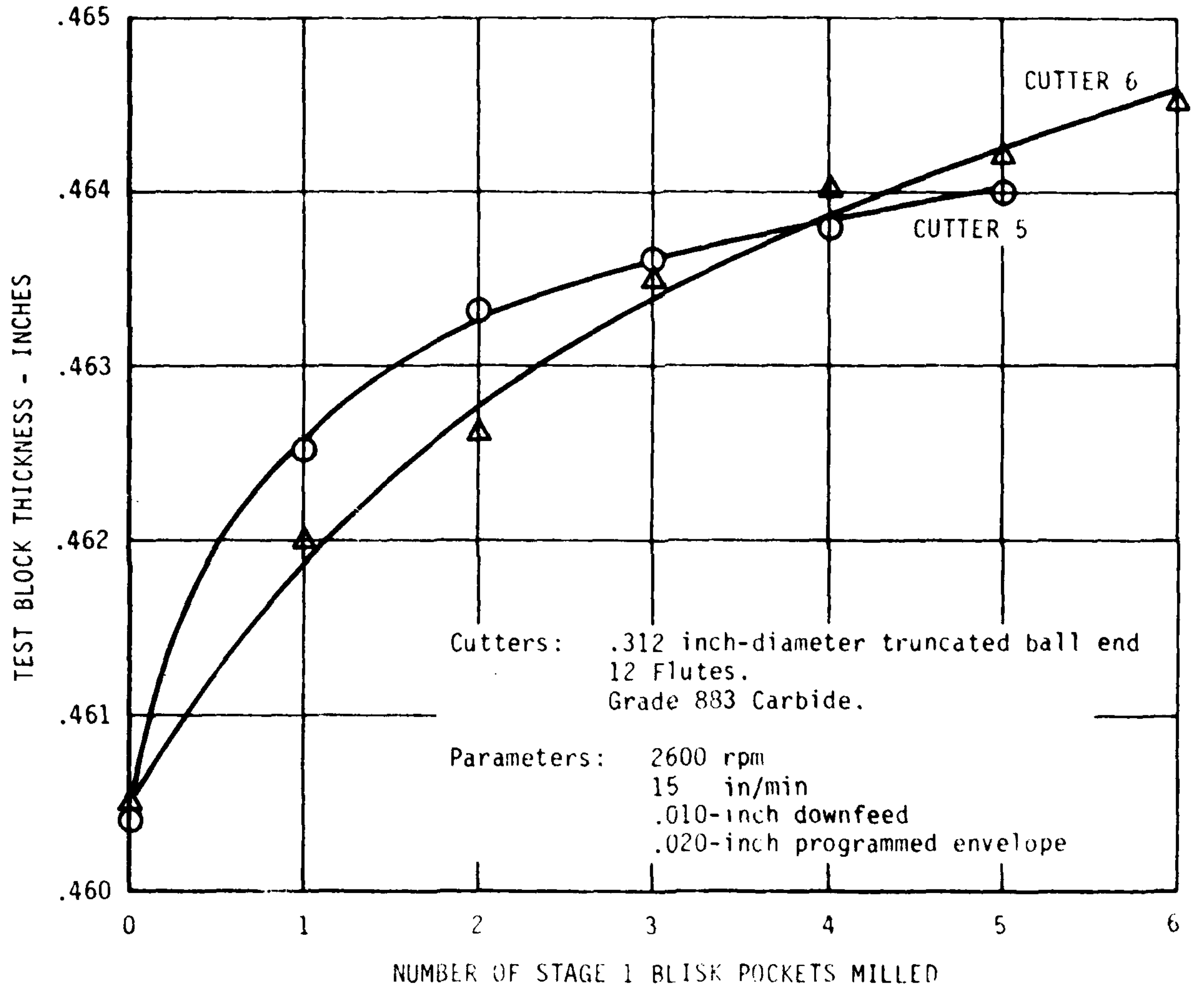
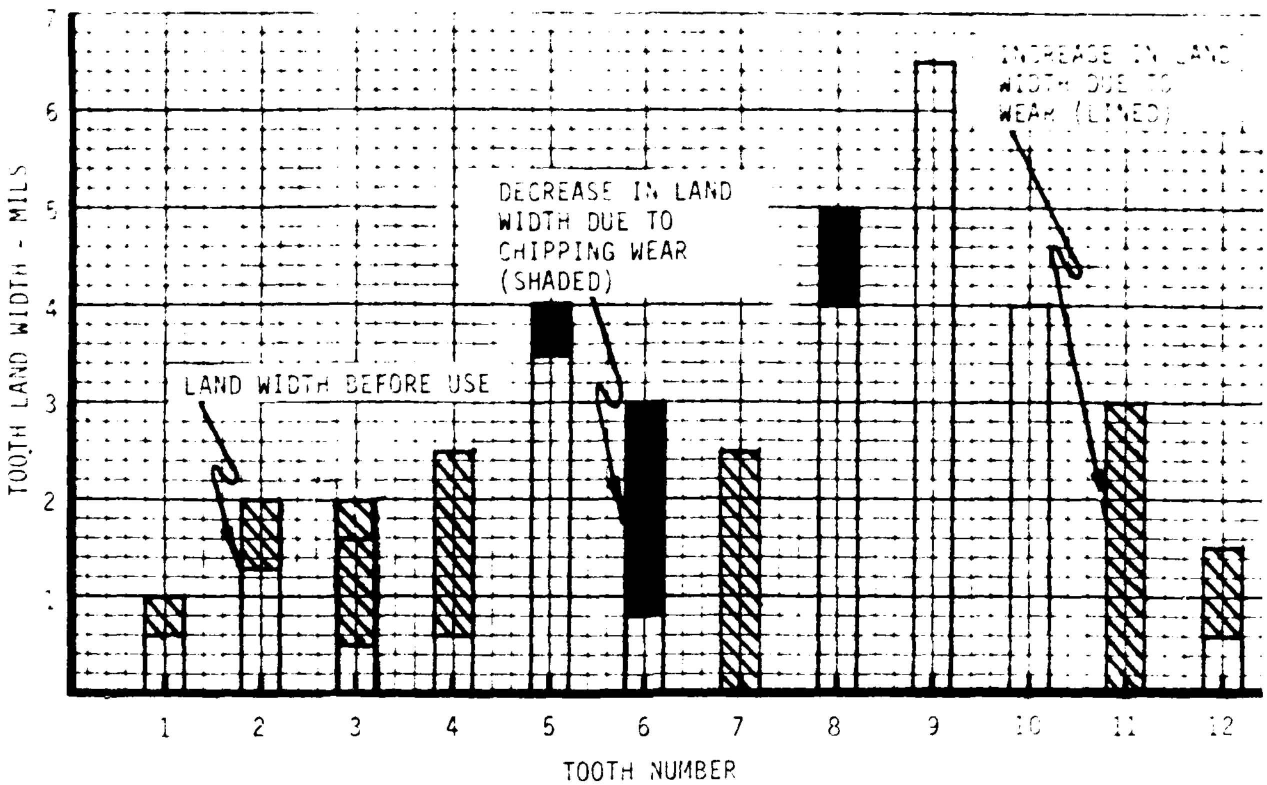



Figure 77. Changes in Airfoil Finish Contour Milling Cutter Wear and Deflection as Indicated by Test Block Thickness.




Cutter - 5/6-inch airfoil finish cutter NO. A1. (see Table 15)
Carbide 883
Geometry given in Table 44.
Pockets Cut - Stage 4, 1 pocket
Parameters -- Given in Table 44.

Measurements of land width made on sphere at 15 degrees from intersection of sphere and cylinder.

Figure 78. Change in Land Width of Teeth on Finish Contour Milling Cutter as Result of Wear.

CONTOUR MILLING
OF
IMPELLER

## CONTOUR MILLING OF IMPELLER

### INTRODUCTION

Impeller contour milling development was carried out in the same way as blisk milling development. INCO 718 material, with characteristics like those required for impellers, was used for all tests.

Alternative processes for rough machining to remove material from between airfoils prior to finish contour milling were considered in the same way as for blisks; processes that were evaluated were electrical discharge machining and electrochemical machining. It was concluded that rough contour milling should be used, for the same reasons that it was selected for blisk.

### ROUGH CONTOUR MILLING

#### Initial Investigation

Tests with INCO 718 test blocks, using a conventional milling machine to make simple straight cuts, indicated that it is feasible to rough contour mill impeller airfoils with cutters as small as 3/16-inch-diameter, using a feed rate of 2.75 in/min and 0.060-inch downfeed, and that the downfeed or feed rate could be greater with 5/16-inch-diameter cutters.

Cutting tests of simulated impeller airfoils were conducted using a tracer mill setup, as shown schematically in Figure 79 (pg 143). The tracer mill was not capable of the complex moves necessary to produce the actual impeller airfoil geometry. Therefore, the change in airfoil height was built into the test peices. Cutters used are described in Table 17.

TABLE 17
CUTTER USED IN INITIAL INVESTIGATION

| | | |
|---|---|---|
| Material | - | Carbide Grade 883 |
| Size | - | 5/16-inch and 1/4-inch diameter |
| Overall Length | - | 2-5/8 inches |
| Flute Length | - | 1 inch |
| Helix Angle | - | 18 degrees |
| Style | - | Right hand spiral; Right hand cut |
| Number of Flutes | - | 4 |
| Corner Radius | - | 1/8 inch |

The test pieces were cut from an available INCO 718 forging with a taper to give the airfoil height variation shown in Figure 80 (pg 144). Simulated airfoils were milled using 5/16-inch-diameter end mill. Downfeeds were limited to 0.060 inch per pass and lineal feed was varied up to 1 inch/min maximum. Attempts at faster feeds resulted in audible vibration and cutter chipping. A test piece was also machined by roughing out two rectangular slots, using 1/4-inch end mills. The strength of these cutters was too low to make the 0.060-inch deep cuts at 1 inch/min., and they broke in the shank area due to excessive cutting force.

It was concluded that the tracer mill was not sufficiently rigid, and that this contributed to excessive cutter vibration which resulted in cutter chipping and fracture. Therefore, additional tests were made using a rigid, heavy duty Cincinnati vertical spindle milling machine to make straight-line cuts on INCO 718

ROUGH CONTOUR MILLING - Continued

test pieces, representing simulated impellers. These included incremental rough milling with 3/16-inch and 5/16-inch-diameter cutters.

The test conditions are shown in Table 18.

TABLE 18
CUTTING CONDITIONS FOR INITIAL INVESTIGATIONS

| | | |
|---|---|---|
| Cutting Speed | - | 74 sft/min; 1500 rpm |
| Cutting Tool: | | |
| End Mill | - | 3/16-inch-dia, 4-flute; and 5/16 inch-dia, 6-flute |
| Radius | - | 0.060 inch |
| Flute Length | - | 1/2 inch |
| Cutting Fluid | - | Sulphochlorinated Oil |
| Depth of Cut | - | Full (3/16-inch-dia) or half (3/32-inch-dia) |
| Cutter Extension | - | 3/4 inch |
| Material | - | INCO 718 at 42 RC |

Test results showed that it is feasible to rough contour mill impellers with cutters as small as 3/16-inch diameter using a feed rate of 2.75 in/min; however, the data indicated that this cutter would be successful only at low force parameters of 0.0005 inch chipload and 0.060 inch downfeed because breakage occurs with higher force parameters. The test data showed that the 5/16 inch cutter can accommodate a chipload of 0.0005 inch, and a downfeed of 0.180 inch. A chipload of 0.001 inch could be used at this downfeed, by the 5/16-inch cutter; however, wear rate was found to increase substantially under this condition.

Additional tests were performed with the vertical spindle milling machine to investigate the use of "stepping" cuts, with the view of minimizing cutter vibration and rough contour milling time. The cutting pattern is shown in Figure 81 (pg 145). The 3/16-inch cutter showed light chipping, and a small uniform wearland increase for the stepping cuts versus full diameter cuts. The 5/16-inch cutter showed essentially no increase in wear rate and cutter chipping was within the wearland. The results of these tests indicated that rough contour milling of impeller airfoils should be performed with stepping cuts to obtain optimum cutter life and optimum machine time.

Rough Contour Milling Plan

Previous investigations indicated that impeller rough contour milling should be done without prior removal of material by a preceding operation. Therefore, it was decided to mill pockets between airfoils using stepping cuts as with blisks. Since airfoil stiffness is much greater for impeller airfoils, as indicated by static deflection tests, it was concluded that the first choice for a milling plan should be to complete rough contour milling of the entire impeller before starting finish contour milling. It was concluded that finish milling should be tried first without a supporting matrix.

ROUGH CONTOUR MILLING - Continued

This plan also provided for leaving only about 15 mils of material to be removed during finish milling, because the waves produced by successive cutter paths should be smaller than for blisks, since smaller downfeed and smaller angle to the airfoil surface would be used. This was also expected to reduce finish contour milling forces and resultant airfoil and cutter deflection.

Cutters

Cutter requirements were established in the same way as for blisks and similar cutters were selected, except that shorter cutter extended length was needed because airfoils are shorter. Shorter cutter extension was also desirable because of the higher cutting forces required with INCO 718 material.

Cutting Forces

Tests like those for blisk rough contour milling were conducted to determine relationships between cutting parameters and cutting forces. Results were used to construct the nomogram shown in Figure 82 (pg 146).

Fixtures

Fixture design like that for blisks was selected for impeller rough and finishing contour milling.

Rough Contour Milling with the Development Machine

Rough contour milling with the development machine began as soon as blisk milling development had progressed far enough to allow beginning impeller milling development. This work was carried out in a way similar to that for blisks.

Breakage was encountered with the 3/16-inch diameter cutters used to remove material from the narrowest areas between impeller airfoils. Cutters made of Carboloy 820 material were tested, and resolved this problem. The Carboloy 820 material has a transverse rupture strength of 450,000 psi, compared with 290,000 psi for the Carboloy 883 material. However, its abrasive wear resistance is lower.

FINISH CONTOUR MILLING

Finish contour milling development was conducted for the impeller much like development was conducted for blisks, both before and after the 5-axis NC milling machine became available.

Normal cutting force was found to be higher than with blisks, since the INCO 718 alloy of which impellers are made is more difficult to machine than the AM355 alloy of which blisks are made. This is partly due to strain hardening of INCO 718, which occurs as chips are removed from the surface. When the depth of cut is small and thin chips are cut, as is the case with finish contour milling, strain hardening proceeds ahead of the cutter so that chips are continually cut from strain hardened material. The importance of strain hardening is indicated in Figure 83 (pg 147).

FINISH CONTOUR MILLING - Continued

Impeller airfoils are much stiffer than blisk airfoils. Therefore, it was concluded that it would be preferable not to use a matrix to support the tips of airfoils where stiffness is lowest, but to select cutting conditions that limited the normal cutting force to a value that would not cause significant airfoil deflection.

Deflection of finished airfoils at locations having the lowest stiffness is shown in Figure 84 (pg 148). Deflection at these locations would be much smaller for rough contour milled airfoils which would be much thicker.

Cutters like those developed for blisks were used. Therefore, cutter deflection characteristics were similar. The cutter used for airfoil and hub finishing is shown in Figure 85 (pg 149).

Impeller finish contour milling was done by finishing a complete airfoil at a time. First all airfoils were produced by rough contour milling. Then the finish contour milling cutter was moved from the leading edge of one airfoil toward the trailing edge, while it milled a path on the surface about 30 mils wide. After finishing that path, it moved across the airfoil to the opposite side, and cut a path on that side of the same width and directly opposite the first path, while moving back to the leading edge. This was repeated to make successive cuts of the same width starting at the tip of the airfoil and progressing down toward the hub surface, until the airfoil was finished. The same procedure was repeated on all airfoils.

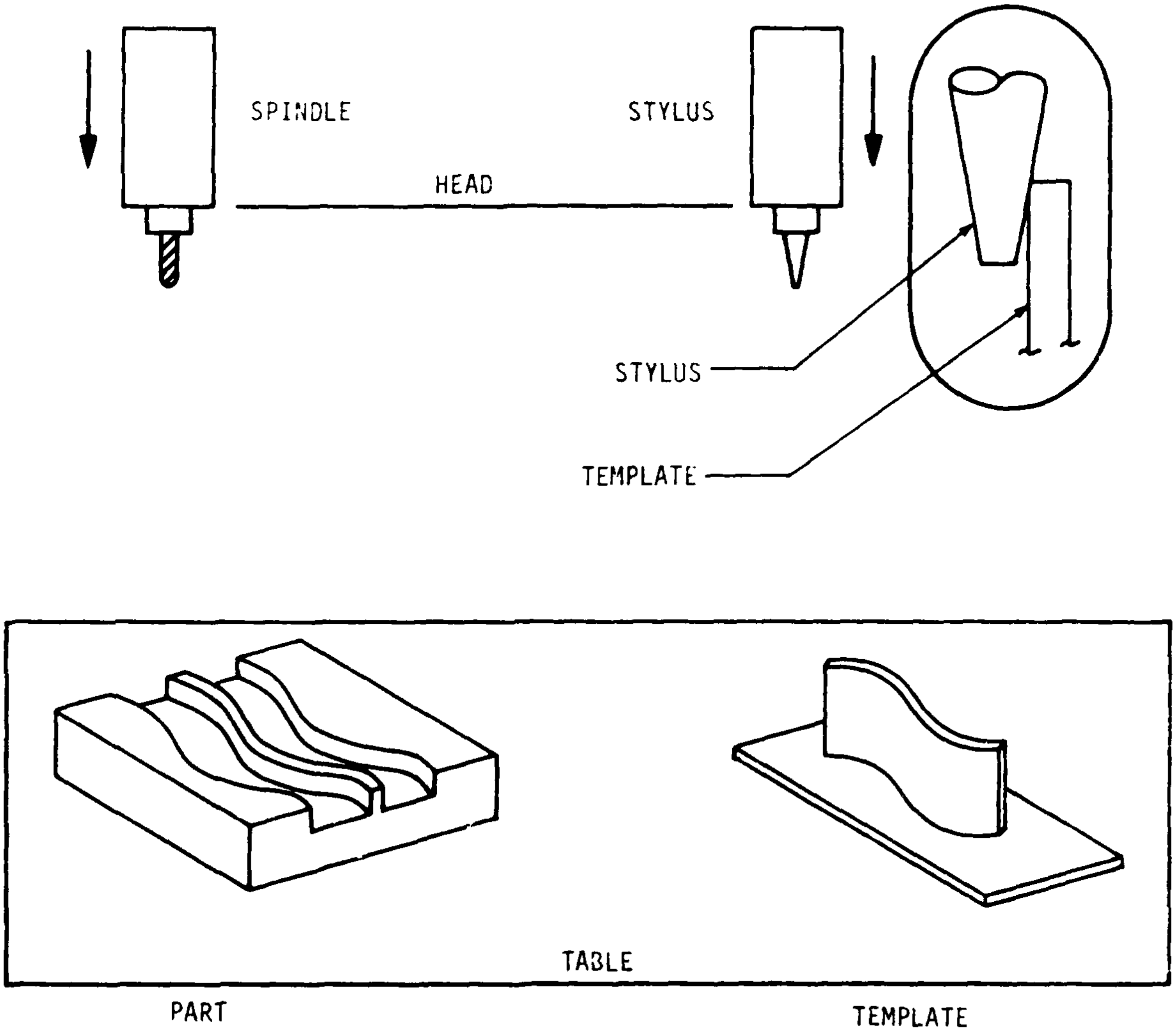
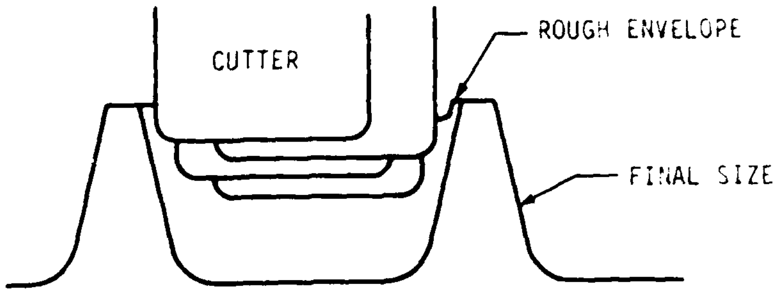
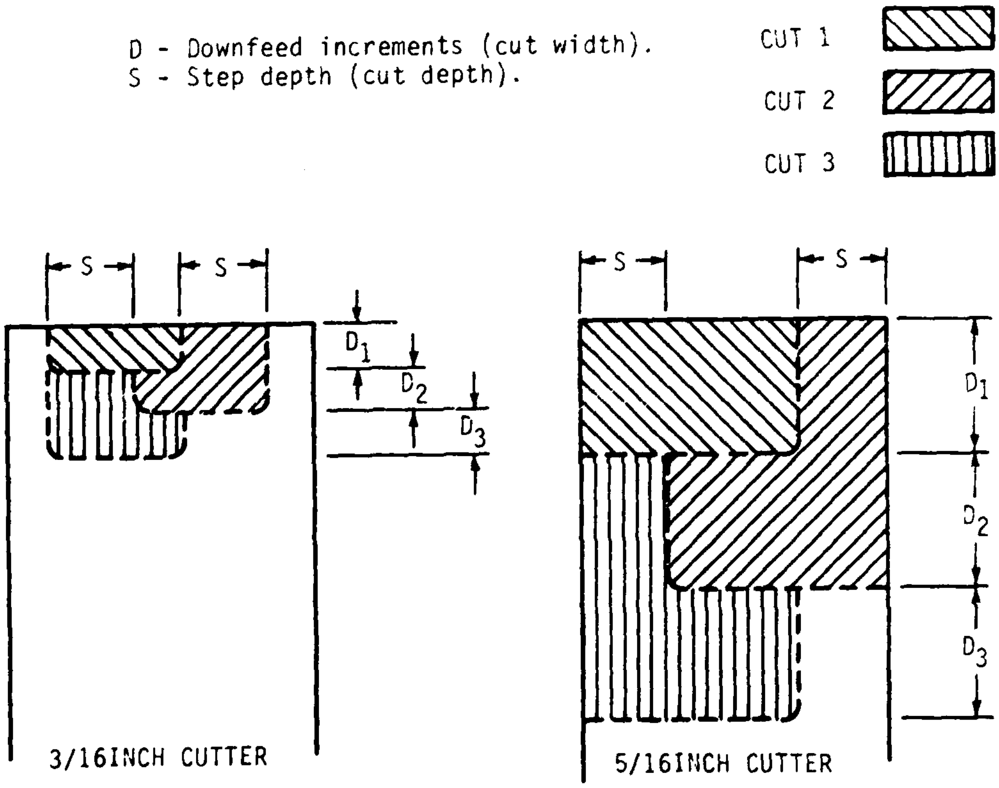



Figure 79. Impeller Airfoil Contour Milling Schematic of Test Setup Using 2-Axis Tracer Machine.


Figure 80. Simulated Impeller Airfoils Produced by Contour Milling in 2-Axis Tracer Machine.

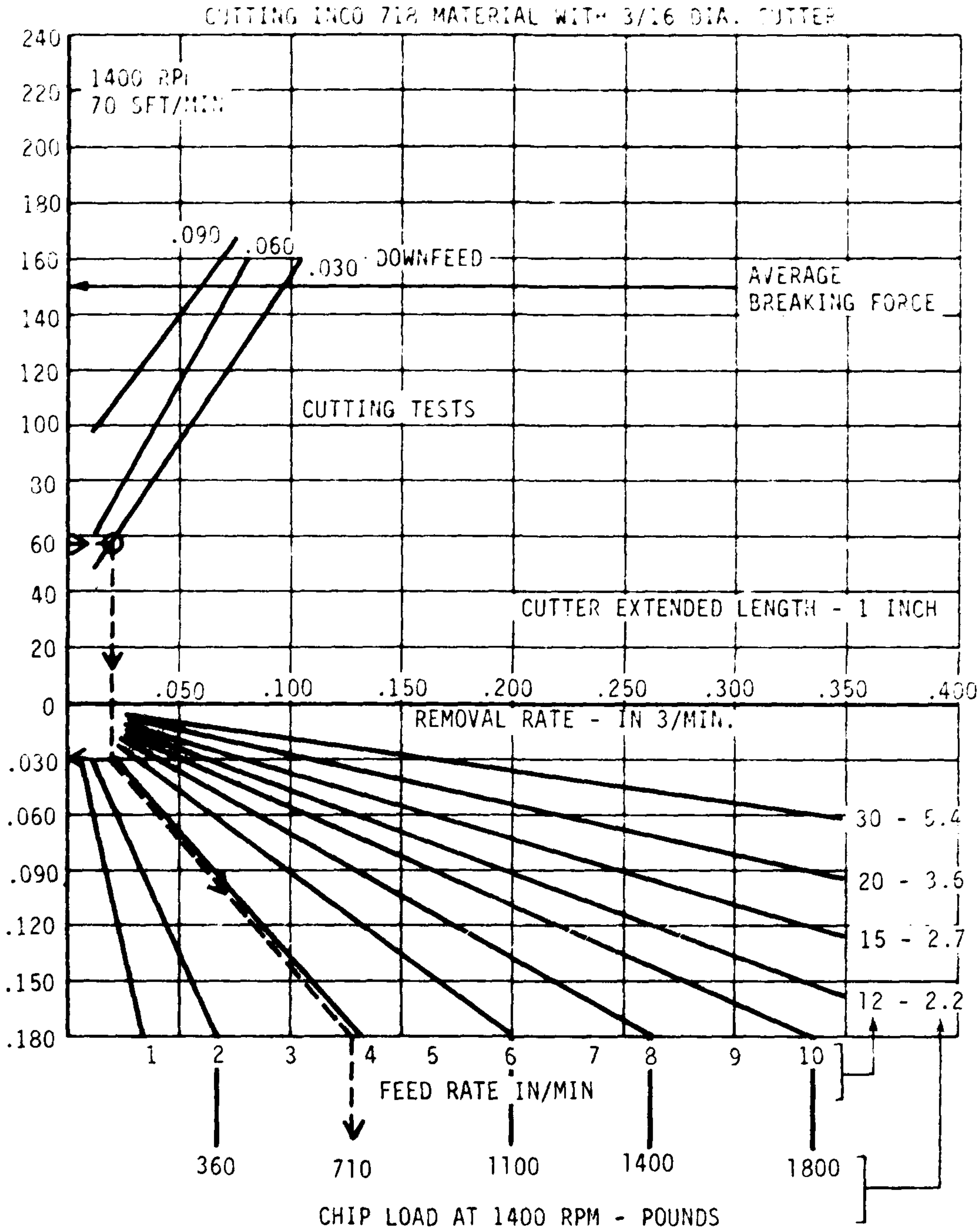



IMPELLER ROUGH CONTOUR MILLING WITH STEPPING CUTS.




b. Stepping Cut Test Procedure.

Figure 81. Impeller Rough Contour Milling.




CUTTER DESCRIPTION: .1875-inch diameter, 4 flutes, 30-degree helix, 0-degree rake, 6-degree relief, .060-inch corner radius, 883 Carboloy.

CUTTING FLUID: Thrall No. 516.

Figure 82. Rough Contour Milling Cutter Force.

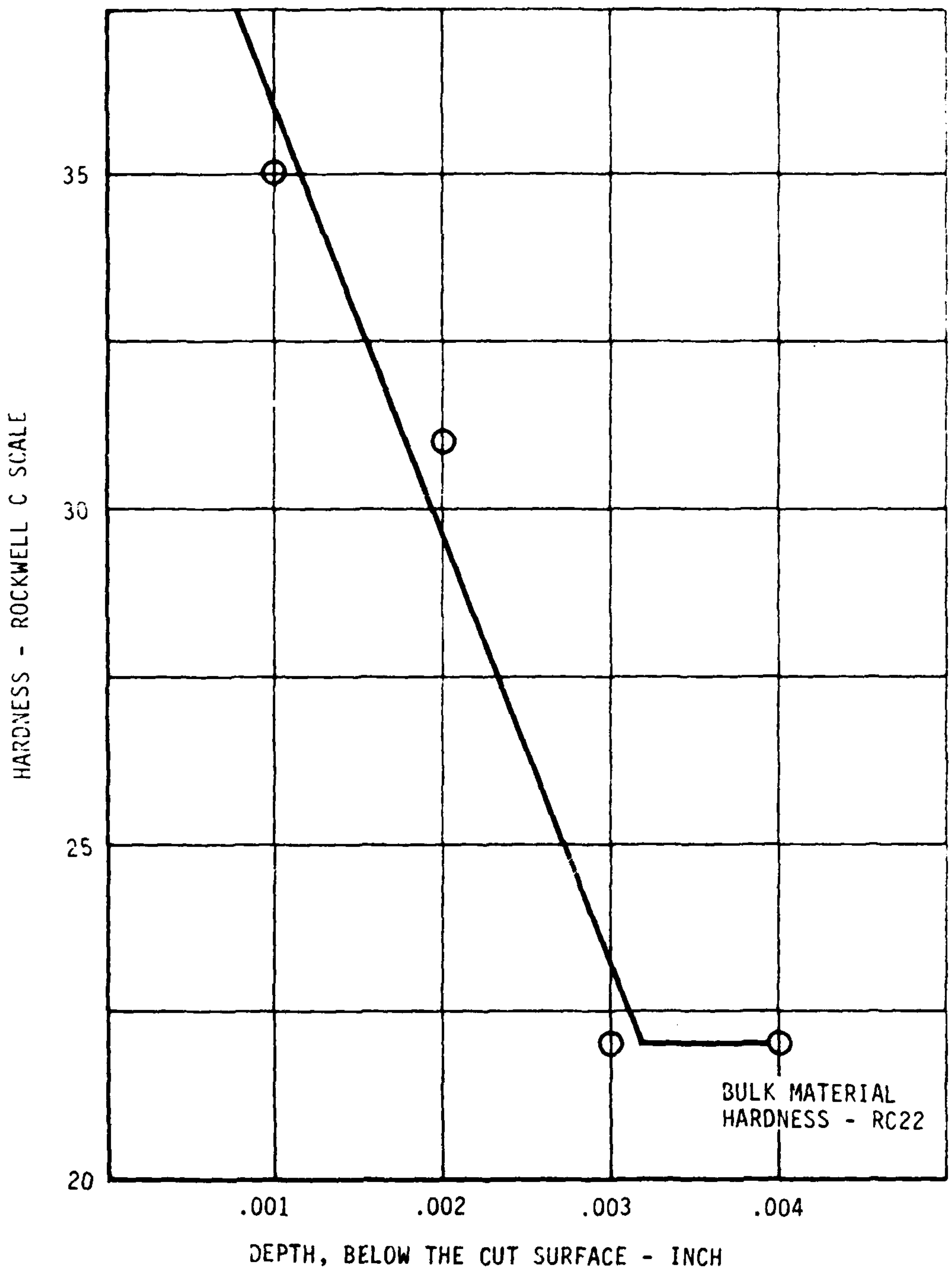
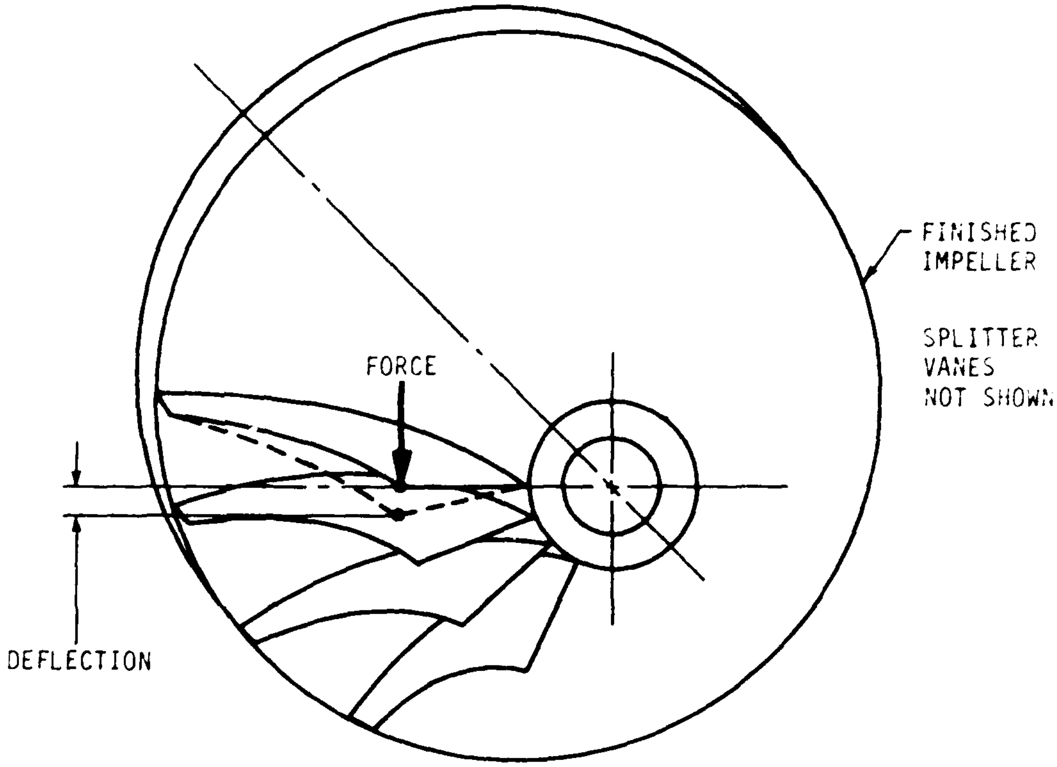



Figure 83. Strain Hardening Due to Impeller Finish Contour Milling.




| Vane No. | Force (pounds) | Deflection (inch) | Deflection/Pound (inch) |
|---|---|---|---|
| | FULL VANES | | |
| 1 | 6 | .0070 | .00115 |
| 20 | 6 | .0052 | .00086 |
| | INTERMEDIATE VANES (FULL SPLITTER) | | |
| 18 | 9.1 | .0012 | .00013 |
| 19 | 9.1 | .0012 | .00013 |

Figure 84. Impeller Airfoil Deflection at Selected Locations.

CARBIDE GRADE - 883

| | |
|---|---|
| Number of Flutes: | 12 |
| Flute Helix: | 30-degree right hand |
| Flute-to-Flute Variance: | .0005 inch max |
| Cylindrical Margin on OD and Radius: | .002 - .003 inch |
| Rake Angle: | 30 ±3 degrees negative |
| Relief Angle: | Standard 45 degrees |

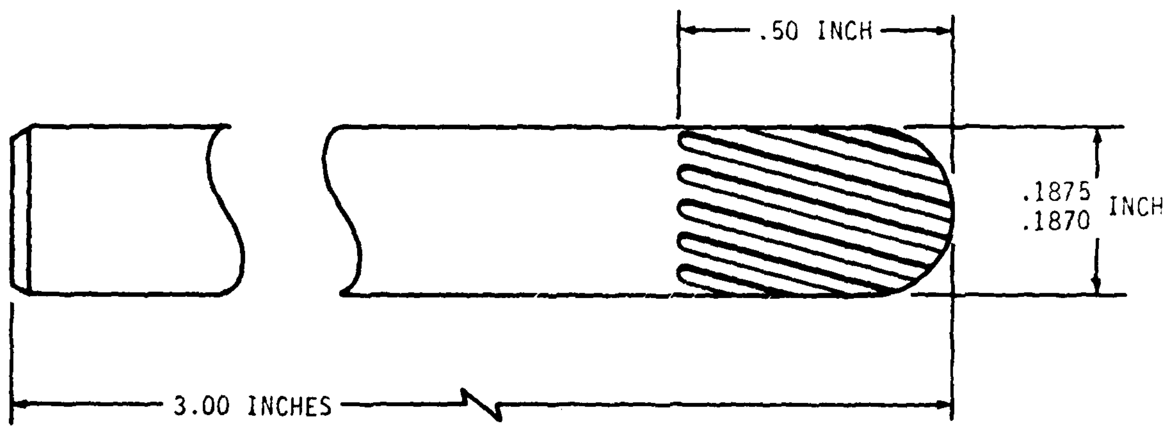



Figure 85. Typical Impeller Airfoil and Hub Finish Contour Milling Cutter Requirements.

BLISK FINISHING
PROCESS DEVELOPMENT

## BLISK FINISHING PROCESS DEVELOPMENT

### INTRODUCTION

The objective of this task was to select and develop the process that would be best suited to produce the final surface texture for airfoils on the blisks and the impeller following NC contour milling.

Several blisk finishing procedures were investigated in this portion of the Blisk and Impeller Process Development Program. These included contour grinding, using cubic boron nitride (CBN) grinding wheels; stationary electrochemical machining (SECM); electro polishing; free abrasive machining; and abrasive flow machining. To obtain data which would allow accurate evaluations of these techniques, it was necessary to provide special tooling and measurement equipment. In those cases where the required tooling was too costly, vendor facilities were utilized.

Process investigations covered the following areas:

1. The ability of each process to produce final surface texture.
2. The relationship between milled surface texture and process parameters, including time to produce final texture.
3. Process control requirements.
4. The suitability of each process for the geometry of each blisk and the impeller.
5. The influence of the process on the integrity of the blisks and impeller.
6. Economic factors, including equipment requirements and opportunity for automation.

The results of these investigations showed that abrasive flow machining (AFM) was the most suitable blisk finishing technique, from the standpoint of effectiveness, ease of implementation and cost. Accordingly, the initial investigations were followed by the design and fabrication of development tooling, extensive process development tests on Stage 1 through 5 blisks and the impeller, and the fabrication of a production AFM machine.

Terms used to describe surface geometry are those used in American Standard ASA B46.1. The term "waviness" is used in this report to describe large surface irregularities between successive cuts. "Roughness" describes smaller irregularities, while "texture" includes waviness and roughness.

### CONTOUR GRINDING STUDY

An investigation was conducted to determine the feasibility of surface finishing with small diameter cubic boron nitride (CBN) or Borazon* grinding wheels. The initial objective was to determine if the surface remaining after contour milling could be ground off with one cut, with acceptable wheel wear and feed rate, to obtain a final surface finish of 32 microinches average amplitude (AA). Trial cuts were made on AM355 and INCO 718 materials with 5/16-inch diameter CBN wheels, using a conventional Moore Jig Grinder. Figure 86 (pg 179) shows the machine with a small CBN grinding wheel and a test piece prepared for end milling.

*General Electric Trademark

CONTOUR GRINDING STUDY - Continued

Accurate readings of spindle speed were obtained by fitting a 15-spline mandrel to the spindle and reading RPM with an E-Put type instrument via a noncontacting pickup.

The CBN Borazon* abrasive wheels are noted for their superior performance in grinding superalloys. Borazon* grinding wheels wear very slowly compared to conventional wheels. The wheels perform at higher g-load ratios; thus, they are capable of removing more metal for a given amount of wheel wear than other abrasive materials.[2] In addition, in this process development project, the restricted space between airfoils requires small vertical-axis wheels capable of holding shape accurately and of giving long life. It was expected that Borazon* could satisfy their requirements better than any other abrasive.

Work performed by others identifies grinding force as having a linear relationship to metal removal rates.[3] However, there is a threshold of force intensity below which no cutting occurs; instead, ploughing occurs. The wheel surface velocity causes a shift in relationships and affects surface roughness.

Force is a difficult parameter to measure since the wheels are quite small and electronic equipment and tooling required to instrument such a test is rather expensive and difficult to use.

To overcome this problem, calculations were used to translate grinding wheel mandrel measured deflection values to grinding forces.

Grinding Tests with CBN Borazon* Wheels

A test plan was generated covering depth of cut ranging from 0.002 to 0.010 inch; lineal feed rates of 0.70 to 2.0 inch per minute; and spindle speeds of 25,000 to 30,000 rpm.

Vertical axis wheels were tested with 1/4-inch diameter shanks and wheel sizes of 5/16 and 1/8-inch diameter. Grit sizes of 60, 80, and 100 were selected for testing in order to establish relationships of metal removal rates, wear and surface roughness. A high grit concentration of 125% was selected to maximize the grain density on the wheel surface, to give maximum latitude in the choice of grain depth of cut.[1] Resin bonding was used since available information indicated that it gives better cutting action.

Figure 87 (pg 180) shows a test sample of AM355 material, together with a CBN Borazon* wheel mounted on a 1/4-inch mandrel. Test results are presented in Table 19 (pg 153).

*General Electric Trademark.

1. Shaw, Milton C., METAL CUTTING PRINCIPLES, MIT PRESS
2. Helmer, J. P., Navarro, N.P., GRINDING SUPERALLOYS WITH BORAZON* CBN ABRASIVE, SME Paper MR 73-736, March 1973
3. Dr. Lindsay, R.P., Navarro, N. P., PRINCIPLES OF GRINDING WITH BORAZON* CBN WHEELS - Part I, Machinery, May-June 1973

TABLE 19
DRY GRIND TEST WITH BORAZON* PLATED WHEEL
AM355 MATERIAL ON MOORE JIG GRINDER

| | Down Grind Pass Number | | | | | Up Grind Pass Number ** | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 3A | 3B | 1 | 2 | 3 | 3A |
| A. Program depth of Cut from Zero Reference - inch | .010 | .010 | .003 | .006 | .010 | .003 | .003 | .003 | .006 |
| B. Table Travel (Cross Feed) (in.) from Zero Reference - inch | .010 | .020 | .023 | .026 | .030 | .003 | .006 | .009 | .012 |
| C. Ground Surface from Zero Reference - inch | .0086 | .0183 | .0213 | .0243 | .0285 | .0025 | .0053 | .008 | .0105 |
| D. Actual Depth of Cut - inch | .0086 | .0097 | .003 | .006 | .0102 | .0025 | .003 | .0025 | .0055 |
| E. Width of Cut - inch | .265 | .185 | .105 | .105 | .105 | .265 | .185 | .105 | .105 |
| F. Delta Program vs Actual - inch | -0014 | -0017 | -0017 | -0017 | -0015 | -0005 | -0005 | -0010 | -0015 |
| G. Feed Rate - in/min | .643 | .497 | .355 | .355 | .355 | 1.86 | 2.00 | 2.00 | 2.00 |
| H. Wheel Speed - rpm | 25,000 | 22,000 | 22,000 | 22,000 | 22,000 | 30,000 | 30,000 | 30,000 | 30,000 |
| I. Tool Deflection inch | .0014 | .0017 | .0017 | .0017 | .0015 | .0005 | .0005 | .001 | .0015 |
| J. Force - pounds | 5.6 | 6.8 | 6.8 | 6.8 | 6.0 | 2.0 | 2.0 | 4.0 | 6.0 |

*General Electric Trademark

** Up Grind - Wheel surface and work surface travel in opposite directions; same direction for down grinding.

CONTOUR GRINDING STUDY - Continued

A computer program was written for the calculation of values of deflection, based on a unit of force of one pound acting at the end of the grinding wheel with a given mandrel diameter and extended length. Deflection has a linear relationship to force, over the range of values of interest, so that any measured amount of deflection, at a specified length, can be converted to force in multiples of one pound using the computer calculated values (see Table 20, (pg 155). These values were used in the analysis of the test grinding data.

Parallel investigations conducted on abrasive flow machining (AFM) showed that AFM is capable of producing a satisfactory final surface texture in less time and with less expensive equipment than is required for contour grinding. Accordingly, the contour grinding study was discontinued after completion of the above tests.

## TABLE 20
## CALCULATED DEFLECTION VALUES OF GRINDING WHEEL MANDREL

```
LIST

*#RUNH *=(CORE=20)
2 FORMAT (5X,F10.6,6X3(F8.4,6X))
3 FORMAT (8X, HDELTX1,10X,5HFORCE,10X,2HEL,10X,4HDIAM)
WRITE (6,3)
FORCE=1.0
DIAM=0.250
EL=.5
YMOD =(0.05*DIAM**4.)
DO 30 I=1,21
IF (I .NE. 1)GOTO 7
EL= .500
GOTO 8
7 EL=EL+.125
8 DELTX1=( FORCE*EL**3.)/(90000000.*YMOD)
WRITE (6,2) DELTX1,FORCE,EL,DIAM
IF(EL .EQ. .3)GOTO 99
30 CONTINUE
99 STOP
END

ready
*RUNH

10/02/75      11.793
```

*DELTX1 = Deflection in inches at extreme end
FORCE = Pounds
EL = Extended length of tool (inches)
DIAM = Mandrel diameter (inches)

| DELTX1 | FORCE | EL | DIAM |
|---|---|---|---|
| 0.000007 | 1.0000 | 0.5000 | 0.2500 |
| 0.000014 | 1.0000 | 0.6250 | 0.2500 |
| 0.000024 | 1.0000 | 0.7500 | 0.2500 |
| 0.000083 | 1.0000 | 0.8750 | 0.2500 |
| 0.000057 | 1.0000 | 1.0000 | 0.2500 |
| 0.000081 | 1.0000 | 1.1250 | 0.2500 |
| 0.000111 | 1.0000 | 1.2500 | 0.2500 |
| 0.000148 | 1.0000 | 1.3750 | 0.2500 |
| 0.000192 | 1.0000 | 1.5000 | 0.2500 |
| 0.000244 | 1.0000 | 1.6250 | 0.2500 |
| 0.000305 | 1.0000 | 1.7500 | 0.2500 |
| 0.000375 | 1.0000 | 1.8750 | 0.2500 |
| 0.000455 | 1.0000 | 2.0000 | 0.2500 |
| 0.000546 | 1.0000 | 2.1250 | 0.2500 |
| 0.000648 | 1.0000 | 2.2500 | 0.2500 |
| 0.000762 | 1.0000 | 2.3750 | 0.2500 |
| 0.000889 | 1.0000 | 2.5000 | 0.2500 |
| 0.001029 | 1.0000 | 2.6250 | 0.2500 |
| 0.001183 | 1.0000 | 2.7500 | 0.2500 |
| 0.001352 | 1.0000 | 2.8750 | 0.2500 |
| 0.001536 | 1.0000 | 3.0000 | 0.2500 |

*Modulus of Elasticity 30 X $10^6$

## ELECTROCHEMICAL MACHINING

Early in the project, a study was initiated to determine the feasibility of using stationary electrochemical machining (SECM) to produce the final surface finish after contour milling. The ECM equipment selected for the project was Cincinnati Milicron 10,000 ampere system, complete with a 500-gallon electrolyte tank and a Sharples centrifuge for electrolyte clarification. The voltage range of this equipment is 0 to 18 volts.

### SECM Test Tooling and Test Plan

Figure 38 (pg 181) Views A, B, and C show the test tool assembly, the test tool with AM355 material serving as a test block, and an additional view of the test block. It should be mentioned that, in conventional ECM, the tool (cathode) is fed toward the work surface (anode) at a constant rate with a constant voltage applied across the gap between the tool and the work surface, and the gap is maintained by the current flow. Thus, work material is removed at a constant rate.[4,5]

It was realized that the use of a moving tool would be very difficult, if not impractical for the impeller and blisk airfoil surfaces, because of surface geometry and because of the limited space between airfoils. If the tool were stationary, it would be possible to avoid problems related to tool movement.

In the case of SECM, tool and part are held in fixed positions, and the gap between them increases as current flows between them. If the voltage applied across these surfaces is held constant, current flow decreases as the gap increases, so the rate at which material is removed from the part surface, decreases. While constant voltage is always used with ECM, it was considered practical to use constant current with SECM, to avoid a reduction of material removal rate by increasing voltage as the gap increases.

When all areas on the part surface are not equidistant from the tool surface, material from areas closest to the tool is removed more rapidly than material further from the tool surface. Therefore, the distance between peaks and valleys on the part surface is reduced and the contour of the part surface is changed in the direction of conformance to the tool surface. The rate at which surface and contour changes proceed depends upon the magnitude of part surface deviation from tool surface contour and upon the gap voltage. The gap voltage, together with gap distance, determine machining current and hence metal removal rate; in other words, the rate at which gap distance increases. The interdependence of these variables was investigated first, in a limited way, to determine the effectiveness of this process in reducing part surface geometry deviations from tool surface geometry, and then the amount of material that must be removed from the part to obtain sufficient reduction of part deviations for satisfactory surface roughness and contour.

4. U. S. Air Force Materials Laboratory Technical Report AFML-TR-72-188.

5. Wilson, J., The PRACTICE AND THEORY OF ELECTROCHEMICAL MACHINING, Published by Wiley-Interscience.

ELECTROCHEMICAL MACHINING - Continued

A test plan was established with the following primary parameters:

Fixed Parameters for All Tests:

Electrolyte Composition - Two pounds sodium nitrate per gallon of water.

Electrolyte Pressure - Inlet at 175 psig and outlet at 25 psig.

Electrolyte Temperature - 70°F to 90°F.

Starting Gap - 0.010 in, as measured at point of narrowest gap.

The above parameters fall within ranges used successfully in other ECM applications.

Variable Parameters for Individual Tests: Voltage, current, and surface geometry.

SECM Test Procedures and Results

Tests were conducted on an AM355 test block which had been prepared using an end mill with 0.060-inch corner radius at an angle of 4 degrees to the surface. The surface texture was generated by feeding the cutter in 0.060-inch steps and the measured waviness height was 1 mil (see View A of Figure 89 (pg 182). The SECM process improved the surface to a waviness height of 0.1 mil, and a surface roughness of six microinches AA (see View B of Figures 89 and Figure 90, pgs 182-183).

Testing was also performed on test blocks with surfaces at an angle to the surface of the stationary electrode. The results of these tests (Figure 91, pg. 184) suggested that both the initial waviness height and the distance between the anodic test block surface and the tool (cathode) are directly related to the amount of material that must be removed from the test block to effect a given reduction in waviness height.

To further examine this relationship, available information based on moving electrode ECM tests with another iron base material was used to construct SECM characteristic curves. These were found to have the same shape as the curves plotted from test data: they indicated that voltage influences only the time required to achieve a given reduction in waviness height.

This suggested that process electrical parameters influence the rate of waviness height reduction and have no other primary effect. Consequently, an analysis was performed of the SECM process to allow a definition of the factors and their relationships, which influence the rate of waviness height reduction. This was accomplished with the aid of the following derived equation:

ELECTROCHEMICAL MACHINING - Continued

$$Z = \frac{D}{G} \cdot g \qquad \text{(Eq 4)}$$

where z = rate at which waviness height is reduced (mils/min)

D = waviness height (mils)

G = average distance between anode and cathode (mils)

g = rate at which G increases (mils/min)

In deriving this equation, the process was assumed to behave in linear fashion, as is usually done in analyses of ECM.[6] However, this is not exactly true, as experimental data in this report indicates, even when measuring inaccuracies are considered.

To allow the equation to give results which correspond well with experimental results, two constants are needed as follows:

$$Z = 1.4 \cdot \frac{D}{G} \cdot g - 0.7 \qquad \text{(Eq 5)}$$

This expression was checked against the ECM nomogram for 17-4PH stainless steel (page 104 of Reference 4). Ten separate checks were made, with maximum deviations of about +11% and -6%, with the majority being 5% or less.

The equation deals with instantaneous values, and the values of all factors in it change with time (including g if voltage, rather than current, is held constant, as is usually done), and changes in all factors are interdependent.

Further tests were subsequently performed to determine the usefulness of SECM for improving surface texture. Table 21 (pg 159) shows the results.

With data from tests summarized as shown in Table 21, it is possible to define the basic characteristics of SECM:

1. The first is that a simple relationship exists between starting gap, small waviness heights, and material. Removal depths needed to achieve waviness reduction to essentially zero, are as shown in Table 22 (pg 159).
2. The second characteristic is that, with greater starting waviness heights, such as up to 0.005 inches, it may be necessary to use a second SECM operation, beginning again with a small starting gap.
3. The third characteristic is that with waviness heights over 0.005, a third SECM operation will most likely be required, even with a very small starting gap for the first operation.

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6. Baldwin, Brown and Gulatti, ELECTROCHEMICAL MACHINING, The Engineer, February 23, 1968.

TABLE 21
WAVINESS HEIGHT REDUCTION BY SECM - ANALYSIS OF TEST DATA

Test Conditions

| | | |
|---|---|---|
| Material | - | AM355 Test Blocks |
| Electrolyte | - | Sodium Nitrate: 2 lb/gal water<br>90°F, 175/25 psi<br>6 to 8 gal/min. |
| Voltage | - | 6 to 15 volts |
| Current | - | 200 to 500 amps |

| Start Gap | Start Waviness Height (in) | End Waviness Height (in) | Material Removal Depth (in) | Ratio = Material Removal Depth ÷ Waviness Height |
|---|---|---|---|---|
| .053 | .0005 | .0000 | .0075 | 15:1 |
| .040 | .0009 | .0000 | .010 | 11:1 |
| .040 | .0008 | .0000 | .008 | 10:1 |
| .040 | .0005 | .0000 | .006 | 12:1 |
| .010 | .005 | .0008 | .024 | 6:1 |
| .010 | .005 | .0003 | .024 | 5:1 |
| .0125 | .0015 | .0000 | .013 | 9:1 |
| .010 | .001 | .0002 | .004 | 5:1 |
| .010 | .001 | .0000 | .007 | 7:1 |
| .010 | .011 | .002 | .022 | 2:1 |
| .005 | .001 | .0001 | .005 | 5:1 |

TABLE 22
WAVINESS REDUCTION REMOVAL DEPTHS

| Range of Starting Gaps (in) | Waviness Height (in) Start Maximum | End | Material Removal Depth in Terms of Waviness Height |
|---|---|---|---|
| 0.040 to 0.050 | 0.001 | 0.000 | 15 times waviness height |
| 0.020 to 0.080 | 0.001 | 0.000 | 10 times waviness height |
| 0.005 to 0.010 | 0.001 | 0.000 | 5 times waviness height |

ELECTROCHEMICAL MACHINING - Continued

Table 23 shows expected SECM capability based on a reasonable starting gap.

TABLE 23
EXPECTED SECM CAPABILITY USING REASONABLE STARTING GAPS

| Starting Gap (in) | Starting Waviness Height (in) | Results of First SECM Operation: End Waviness Height (in) | Results of First SECM Operation: Depth of Material (in) | Number of SECM Operations to Achieve 0.000 in Waviness Height |
|---|---|---|---|---|
| 0.010 | Up to 0.0015 | 0.000 | 0.015 | 1 |
| 0.010 | 0.0015 to 0.005 | 0.000 to 0.001 | 0.025 | 1 or 2 |
| 0.010 | 0.005 to 0.011 | 0.001 to 0.002 | 0.025 | 2 or 3 |

## Analysis of Blisk Airfoil Electrical Heating

Machining current must flow from a power supply to the tool cathode, through the electrolyte in the machining gap, and then into the airfoil surface. All current must then flow out of the airfoil, back to the power supply. The best path from the standpoint of tool design, is for the current to flow from the airfoil to the disk part of the blisk, and then through contact surfaces in the tooling, back to the power supply.

This path requires that all current flow through the airfoil root section. The resistance of the airfoil material tends to cause electrical heating. The heating was evaluated by a simple analysis of blisk Stage 2, which showed that with a current density of 500 amp/in$^2$, approximately 10 Btu/min would be produced. Approximately 1-1/2 gal/min of electrolyte would carry this heat away with about a 1°F temperature rise. Flow rates used in tests described in the SECM Test Procedures and Results section (pgs 157-158) were between 5 and 9 gal/min. These numbers have an order of magnitude accuracy and indicate that electrical heating will not be sufficiently great to require complicated heat transfer features in an SECM tool, nor to cause any reduction in the integrity of airfoil properties, nor to require any extensive heating tests.

## Study of SECM tool Design Concepts

A study of tool design concepts for blisk airfoil finishing was made with the following results:

1. The tool (see Figure 92, pg 185) would provide for simultaneous machining of both sides of one or more blades, the root radii and a portion of the platform area on each side of the blades. This would require two electrodes (cathodes), one on each side of the blade.

ELECTROCHEMICAL MACHINING - Continued

2. An index table would locate and support the semifinished blisk, and position the blade with respect to the contoured electrodes.

3. Electrodes would be moved radially inward on a track which allows for the twist in the blade.

4. When electrodes are in position, they would be locked in place between two plates, which would also provide the electrolyte connections.

5. Manual work elements would be limited to loading the part, starting the SECM operation, and unloading the part. Other functions would be automated, including part clamping, electrode positioning, control of the amount of material removed (by measuring ampere minutes), and part indexing to machine successive blades.

Conclusions for SECM Development

This investigation indicated the development of an SECM system would be a major undertaking. Extensive development was anticipated to produce a machine that would be capable of providing the required airfoil edge and chord geometry. In addition, it could not be determined if the final surface produced by SECM would reduce airfoil fatigue characteristics until development was completed. The magnitude of required work, and the uncertainty of potential benefits, indicated that no further effort would be expended on the development of the SECM process.

ELECTRO POLISHING

During the early phases of the process development project, consideration was given to the desirability of investigating electro polishing (EP) as a means of producing the final surface texture after finish contour milling.

Electro polishing is similar to stationary ECM (SECM), in that both methods use an electolyte, a cathode located some distance from an anodic work piece and low dc voltage. However, the distance between the cathode surface and the surface of the anodic work piece is much greater with EP. In addition, EP uses acid electrolyte and much lower current densities.

Large distances between the cathode and work surface eliminate the need for very precise cathode geometry; they also avoid the need for precise location of the work piece surface with respect to the cathode surface.

Finally, EP concentrates on surface improvement without requiring removal of a significant amount of material from the work piece, and therefore has little effect on work piece geometry.

ELECTROCHEMICAL POLISHING - Continued

Electro Polishing Feasibility Tests

Feasibility tests were performed by three vendors using test blocks with waviness heights of about 0.0003 in. Results were evaluated and it was found that EP substantially improved surface roughness, but did not significantly affect waviness. The vendors were:

| | | | |
|---|---|---|---|
| 1 | MacDermid Inc. | - | Waterbury, Connecticut |
| 2 | Hubbard Hall Co. | - | Waterbury, Connecticut |
| 3 | Molectrics, Canada | - | Waterloo, Ontario |

Electro Polishing Tool and Tests

No information is available on EP when used with parts displaying geometry like blisks and impellers. The large distances between cathode and work piece surfaces, commonly used with EP, allow the use of electrodes with simple geometry. However, the distance between cathode surface and various points on blisk airfoil surfaces would be quite different, and it was expected that this could result in satisfactory improvement of airfoil surfaces closest to the cathode, or surfaces in direct line with the cathode, but not of surfaces furthest from or not in line with the cathode. Problems of this kind are known to exist with EP.[7].

When using larger distances, it has been reported that EP can reduce roughness heights ranging between 130 micro inches and 250 micro inches, to heights of between 60 microinches and 130 microinches.[7] This magnitude of improvement is approximately that needed to change the roughness of a milled surface, with a roughness of 60 microinches, to a surface with 22 microinches AA roughness.

A test tool was designed for investigating conditions which would exist when using EP to finish blisk airfoil surfaces, with a simple thin cathode located midway between airfoils so that all points on the airfoil surfaces would be essentially equidistant from the cathode (see Figure 93, pg 186). With such an arrangement, the distance between cathode and airfoil surfaces would be about 1/4 inch, as provided in the tool.

Tests were also performed at Molectrics, Canada on blocks prepared with milling cutters at downfeeds of 0.020 and 0.010 inch. Surface roughness was 40 to 75 micro inches. The anode-to-cathode distance was maintained at 0.20 inch.

The data shown in Table 24 (pg 163), shows no measurable reduction in the waviness height. Visual examination at 5X magnification confirmed that material was removed from both valleys and peaks.

Some surface roughness improvement did occur in almost every case. This improvement is relatively small and even when starting with low roughness, such as 50 to 60 micro inches AA as measured perpendicular to the waves, the resulting surface was not improved to the design requirement of 32 microinches AA or better.

7. Fedot'ev, N.P., Grilikhes, S. Ya. (Translated by Behr, A.), ELECTROPOLISHING, ANODIZING AND ELECTROLYTIC PICKLING OF METALS, Robert Draper Ltd., Great Britain.

ELECTROCHEMICAL POLISHING - Continued

The results of the tests indicated that considerable development would be required to determine if EP can be adapted to produce acceptable surface texture, and that a very smooth texture must first be produced by finish contour milling. It was not known if the surface produced by EP would significantly reduce airfoil fatigue characteristics. If this were to happen, a mechanical surface finishing process would be required after EP to overcome such reduction. The uncertain magnitude of this work and the uncertainty of potential benefits indicated that no further investigation should be made. Accordingly, the investigation of the EP surface finishing process was discontinued.

TABLE 24
ELECTRO POLISH TEST DATA

| Block No. | Voltage | Time (min) | Current Density $(amp/in^2)$ | Temp Start (°F) | Temp Finish (°F) | Waviness Height (Inches) Before | After | Surface Roughness (Micro-Inches AA) Before | After | Depth Material Removed |
|---|---|---|---|---|---|---|---|---|---|---|
| 9B | 8-9 | 6 | 560 | 145 | 154 | .0004 | .0004 | 80 $\perp$<br>35 $\parallel$ | 60 $\perp$<br>30 $\parallel$ | .0006 |
| 9C | 8-9 | 3 | 560 | 145 | 154 | .0003 | .0003 | 58 $\perp$<br>42 $\parallel$ | 44 $\perp$<br>46 $\parallel$ | .0004 |
| 10B | 8-9 | 6 | 560 | 145 | 154 | .0004 | .0004 | 50 $\perp$<br>48 $\parallel$ | 40 $\perp$<br>35 $\parallel$ | .0007 |
| 10C | 8-9 | 3 | 560 | 145 | 154 | .0003 | .0003 | 70 $\perp$<br>32 $\parallel$ | 38 $\perp$<br>42 $\parallel$ | .0004 |
| 11A | 8-9 | 3 | 560 | 145 | 154 | .0002 | .0002 | 58 $\perp$<br>48 $\parallel$ | 36 $\perp$<br>28 $\parallel$ | .0004 |
| 11C | 8-9 | 6 | 560 | 145 | 154 | .0003 | .0002 | 58 $\perp$<br>48 $\parallel$ | 45 $\perp$<br>45 $\parallel$ | .0008 |
| 12A | 8-9 | 3 | 560 | 145 | 154 | .0002 | .0002 | 53 $\perp$<br>40 $\parallel$ | 44 $\perp$<br>28 $\parallel$ | .0005 |
| 12C | 8-9 | 6 | 560 | 145 | 154 | .0002 | .0002 | 60 $\perp$<br>40 $\parallel$ | 48 $\perp$<br>38 $\parallel$ | .0008 |

NOTES:

The 1-1/4 x 7/8 inch test blocks were processed in the tooling shown in Figure 93(pg 186) with anode to cathode distance set at 0.20 inch.

Roughness data marked  was taken perpendicular to the waves while data marked was taken parallel to the waves. Measurements were taken with a Profilometer set at 0.030-inch cut off. Waviness height was measured with a ContouReader.

Current density data are based on observed current as reported by Molectrics, Canada and are included for record purposes only. They are considered to be in error, and probably two orders of magnitude higher than actual current density.

## FREE ABRASIVE MACHINING

The term Free Abrasive Machining (FAM) describes processes which produce sliding contact of free abrasive particles with the surfaces of a part, to improve the surface texture. Particles used in the process may be selected from a wide range of sizes, geometry and composition. Relative motion and forces between the two are induced by agitating the part or the container holding the part and abrasive, or by rotating the container or part, or by combinations of these. Liquid such as water may be used. Tumbling is a widely used FAM process. Part geometry can greatly influence the effectiveness of FAM, and the type of motion needed to produce a consistenct surface texture.

Following a search for promising FAM processes and capable vendors, it was concluded that Centrifugal Barrel Finishing,[8] also known as Harperizing, and Almco Spindle Finishing [9] should be investigated further for blisk and airfoil finishing. Feasibility tests, on AM355 blocks, were made by Almco. Results showed that the process was capable of reducing large waviness heights of 0.003 inch down to essentially zero, with some alteration of geometry, and with removal of material from surface peaks in preference to valleys.

### Free Abrasive Machining Tests

Test samples, representative of actual blisk blades, positioned in the same manner as on a blisk, were prepared for process tests. The actual test piece, chosen for the process, consisted of the lower section of AM355 blades from a J85 jet engine Stage 1 blisk in production at the General Electric, Rutland, Vermont, plant. The blades were mounted on a special disk, as shown in Figure 94 (pg 187).

Radial lines approximately 0.001-inch deep were scribed at 1/4-inch intervals on the blade convex and concave surfaces and in the blade root radius. It was anticipated that visual examination of these lines, during tests, would indicate the effectiveness of the FAM process for uniform material removal.

Initial tests were performed on simulated blisk airfoils at the Harper Buffing Machine Co. laboratory to evaluate the capability of the Harperizing process. The principle of operation of the process is shown in Figure 95 (pg 188). In addition, tests were conducted in the Almco Laboratory of the King-Seeley Thermos Co. The operation of the Almco Spindle finishing equipment is described in Figure 96 (pg 189).

FAM tests were made on two airfoils designated Type S and Type SM. The Type S airfoil is that shown in Figure 94 (pg 187), whereas the Type SM is a Type S airfoil with portions of the surface roughened with a 3/8-inch-diameter burr, to represent a milled surface produced with a 0.020-inch downfeed. The Type SM blades were used for investigation of surface texture changes, as opposed to over-all geometry as was the case with the Type S blades.

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8. Hignett, J. B., CAPABILITIES AND LIMITATIONS OF CENTRIFUGAL BARREL FINISHING, SME Technical Paper - MR75-834.

9. Brandt, J. N., SPINDLE FINISHING - CAPABILITIES AND LIMITATIONS, SME Technical Paper MR 75-832.

FREE ABRASIVE MACHINING - Continued

A total of seven different media were used in the tests, as follows:

1. Almco Media 16A is simply 16 grit aluminum oxide.

2. Almco Media 1/4-in XP is a preform made of a mixture of silicone flour and plastic which is cast in the shape of a pyramid with roughly 1/4-inch long sides.

3. Harper Media 651 is a fused aluminum oxide with varying grit size ranging from 12 to smaller sizes.

4. Harper Media 748-1/8 is a cylindrical preform 1/8-inch diameter and 1/4-inch long with the ends cut at 45 degrees. It contains a coarse abrasive.

5. Harper Media Titan is a very fine light powder which is run dry and used for polishing. It consists of corn cob particles of 180-grit size and aluminum oxide of 400-grit size.

6. Harper Media 355T is a preform of triangular shape with abrasive less coarse than the 748; the largest dimension was 3/16 inch.

7. The 748-3/16 is the same as 748-1/8 except 3/16-inch diameter.

In the Almco tests, water was used to keep the media wet and to flush debris away. In the Harper tests, water was used with a wetting agent to keep the media wet and submerged, excepting the Titan polishing media, which was used dry.

All Almco tests were performed with the outside diameter of the simulated blisk located 3-1/2 inches from the wall of the tub and the closest point of the airfoil at 2 inches from the bottom. The spindle was set at an angle of 7 degrees with respect to the wall of the tub in the direction away from the tub and at 22 degrees into the mass of moving media. The drum rotated counter-clockwise at 600 feet per minute (ft/min) at the outside diameter of the drum. The spindle rotated clockwise at 31 rpm. The spindle angles were selected by observing the action of the media against the simulated blisk in a partially filled drum.

In the Harperizing tests, the media flow over airfoil surfaces was similar to the flow with Almco Spindle Finishing; however, the media velocities relative to the airfoil surfaces, and the forces of the media against the airfoils were different. In Harperizing, the relative velocities result only from the speed of the drum; in Almco Spindle Finishing, the airfoil velocity caused by the speed of the spindle is in addition to, or subtracted from the velocity of the media particles resulting from the speed of the drum. Flow conditions over an airfoil also change drastically as the airfoil is rotated fthrough a full revolution.

FREE ABRASIVE MACHINING - Continued

Test Results

The results of the above tests are summarized in Table 25 (pg 167). The lowest surface roughness, with unshielded airfoils, was obtained in Almco Tests 3 and 5 and Harper Tests 6, 8, and 9. Discussion will be confined to these tests.

The roughest surface areas exceeded the design requirement of 32 microinches AA, and the smoothest areas met or were well below this requirement. The lowest roughness always occurred at the airfoil trailing edge near the tip where depth of material removed was greatest. Highest roughness occurred near the platform.

Differences between maximum and minimum thickness change was never less than 3 mils (Harper Test 8) and was as much as 8 mils (Harper Test 9), giving a minimum variability of at least 1.5 mils. Minimum thickness change was 1 mil (depth of material removed 1/2 mil) which is desirable, but the lowest maximum was 4 mils (depth of material removed 2 mils) which is two-thirds of the airfoil tolerance envelope and is, therefore, larger than desirable.

Chord reduction was as great as 80 mils, and not less than 25 mils. Differences were generally about 30 mils, when comparing chord reduction at different sections on the same airfoil. Shielding (Figure 97, pg 190) can make chord reduction much less (Almco Tests 7 and 8) although considerable investigation would be needed to determine its usefulness.

In conclusion, it can be stated that surface texture produced by the above tests did not meet design requirements. Major geometry changes accompanied texture improvements. The investigations did not indicate a reasonable probability that FAM can be used as a final surface finishing process for blisk or impeller airfoils. Further development might have revealed conditions under which FAM could be used; this could have included the generation of special edge geometry, with surface texture very close to the design requirement, by finish contour milling. The magnitude of the development required to determine if FAM could be used and the possibility of higher finish contour milling costs, indicated that no further investigation of FAM was justified.

ABRASIVE FLOW MACHINING

Abrasive flow machining (AFM) occurs when a media consisting of a viscous vehicle, carrying large quantities of abrasive grit, flows under pressure across a surface from which material is to be removed. To obtain high media pressure against a flat or contoured work surface, the media must be contained within a narrow flow path by a flow restriction (see Figure 98, pg 191).

Abrasive flow machining is currently used to remove burrs, size holes, remove EDM recast layers, radius sharp edges and for making limited improvements in surface roughness. Considerable knowledge is available concerning the use of AFM for these applications.[10,11].

10. Perry, W. B., Properties and Capabilities of LOW PRESSURE ABRASIVE FLOW MEDIA, SME Technical Paper MR75-831.

11. Rhoades, L.J., Siwert, D.E., EXTRUDE HONE DEBURRING: THEORY AND APPLICATION OF ABRASIVE FINISHING. SME Technical Paper MR75-842.

TABLE 25
BLISK FREE ABRASIVE MACHINING
SIMULATED AIRFOIL TEST CONDITIONS AND RESULTS

| Equipment | Test No. | Airfoil Type | Media | Total Time (hr) | Chord Change (in) B-B | C-C | D-D | E-E | Thickness Change Near Stacking Axis (in) B-B | C-C | D-D | E-E | Maximum Change In Thickness Inch | Location | Average Amplitude Surface Roughness (microinch) Start | End Max. | Min. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Almco | 1 | SM | 16A | 2 | - | - | - | - | - | - | - | - | - | - | 120 | 120 | 60 |
| Almco | 2 | SM | 1/4"XP | 2 | - | - | - | - | - | - | - | - | - | - | 120 | 40 | 20 |
| Almco | 3 | S | 1/4"XP | 2 | .030 | .032 | .040 | .080 | .003 | .002 | .001 | .006 | .007 | TE | 90 | 35 | 15 |
| Almco | 4 | SM | 1/4"XP | 1 | - | - | - | - | - | - | - | - | - | - | 120 | 70 | 35 |
| Almco | 5 | S | 1/4"XP | 1 | .025 | .025 | .028 | .070 | .006 | .003 | .002 | .006 | .007 | TE | 90 | 50 | 30 |
| Almco | 6 | SM* | 1/4"XP | 2 | - | - | - | - | - | - | - | - | - | - | 120 | 80 | 40 |
| Almco | 7 | S* | 1/4"XP | 2 | .009 | .007 | .000 | .000 | .004 | .000 | .000 | .002 | .009 | TE | 90 | 70 | 25 |
| Almco | 8 | S* | 1/4"XP | 2 | - | - | - | .004 | - | - | - | .006 | .005 | TE | 90 | 45 | 30 |
| Harper | 1 | S | 651 | 1/2 | .000 | .000 | .000 | .008 | .000 | .000 | .00 | .001 | .001 | TE | 90 | 60 | 40 |
| Harper | 2 | S | 748 1/8 | 1 | .012 | - | - | .011 | - | - | - | - | - | - | 120 | 65 | 40 |
| Harper | 3 | SM | Titan | 2 | - | - | - | - | - | - | - | - | - | - | 120 | 70 | 20 |
| Harper | 4 | S | Titan | 2 | .004 | .008 | .010 | .012 | .003 | .003 | .001 | .002 | .005 | TE | 90 | 60 | 30 |
| Harper | 5 | SM | 355T | 3 | - | - | - | - | - | - | - | - | - | - | 128 | 120 | 60 |
| Harper | 6 | S | 355T | 3 | .030 | .035 | .050 | .060 | .001 | .001 | .001 | .001 | .007 | TE | 90 | 40 | 30 |
| Harper | 7 | S | 651 | 2 | .010 | .015 | .032 | .025 | .001 | .003 | .004 | .004 | .004 | - | 90 | 55 | 40 |
| | | | 748 3/16 | | | | | | | | | | | | | | |
| Harper | 8 | S | Titan | 2 | .035 | .030 | .036 | .060 | .081 | .001 | .001 | .001 | .004 | TE | 90 | 45 | 20 |
| Harper | 9 | S | Titan | 6 | .045 | .034 | .040 | .080 | .002 | .003 | .004 | .004 | .010 | TE | 90 | 35 | 15 |

*These airfoils were shielded at the leading edge and rotated in one direction only (see Figure 97, pg 190).

ABRASIVE FLOW MACHINING - Continued

However, very limited knowledge was available at the outset of this study for improvement of the texture of comparatively large surfaces, such as blisks and the impeller, where surface waviness and roughness must be substantially reduced while maintaining tight geometric tolerances.

Therefore, new investigation was required of process characteristics before it could be judged whether AFM should be tested with actual or simulated blisk and impeller geometry, and before a sound plan could be devised for such tests.

The abrasive media, used in AFM, are of prime importance. Grit sizes ranging from 20 to 500 are available, together with compounds of various viscosities.

Initial AFM Tests

Arrangements were made with two vendors for AFM tests on AM355 test blocks. These were: Dynetics Corporation of Woburn, Massachusetts; and Extrude Hone Corporation in Irwin, Pennsylvania. The test procedure involved loading the AFM machine with a known quantity of abrasive media, positioning the tool containing the test piece in the machine, and passing the media through the tool for a predetermined number of cycles. The test piece was then removed and measurements made of changes in test piece thickness and waviness height.

A typical test block, before and after AFM, is shown in Figure 99 (pg 192) together with a test tool. Initial tests at Dynetics indicated that hardened steel showed less wear than nylon or ceramic material as a restricting tool surface. These tests also indicated that AFM can remove major surface waviness and produce a very satisfactory surface texture, as shown in Figure 100 (pg 193).

Additional tests were performed at Dynetics with the following objectives:

1. To determine the ability of AFM to improve surface texture.

2. To determine the depth of material that must be removed to produce an acceptable final finish.

3. To evaluate the effect of AFM on part geometry.

The test parameters were: three grades of silicon carbide abrasive, three gap levels (distance between the test block and the restriction), two pressure levels, and two media flow directions (parallel and perpendicular to the surface waves produced by contour milling cuts). The test results are summarized in Table 26 (pg 169) and Figures 101-102 (pgs 194-195). Surface texture measurements were performed with a ContouReader. The following conclusions were drawn from these tests:

1. Abrasive Flow Machining is capable of reducing waviness height from as high as 0.003 inch down to essentially zero, and can produce surface roughness better than 32-microinch AA.

TABLE 26

SUMMARY OF AFM TESTS WITH TEST BLOCKS

| Test No. | Media | Start Gap S-Small M-Medium L-Large | Pressure (psi) | Direction of Flow $\perp$ or $\parallel$ | Number of Cycles | Time (sec) | Depth of Material Removed (inch) | End Waviness Height (inch) | Surface Roughness ($\mu$/in. AA) | Surface Roughness ($\mu$/in. AA) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | A | S | 500 | $\parallel$ | 50 | 711 | .005 | .0005 | - | - |
| 2 | A | M | 500 | $\parallel$ | 50 | 348 | .005 | .0010 | - | - |
| 3 | A | S | 450 | $\perp$ | 50 | 642 | .005 | .0002 | - | - |
| 4 | A | M | 450 | $\perp$ | 50 | 248 | .004 | .0003 | - | - |
| 5 | B | M | 450 | $\parallel$ | 50 | 450 | .005 | .0005 | - | - |
| 6 | B | L | 450 | $\parallel$ | 50 | 587 | .002 | .0008 | - | - |
| 7 | B | L | 450 | $\perp$ | 50 | 549 | .005 | .0000 | - | - |
| 8 | A | S | 450 | $\parallel$ | 50 | 727 | .006 | 0010 | 5 | 65 |
| 9 | A | S | 450 | $\perp$ | 50 | 694 | .005 | .0000 | 9 | 14 |
| 10 | A | S | 350 | $\perp$ | 50 | 1829 | .005 | .0002 | 11 | 16 |
| 11 | A | S | 450 | $\parallel$ | 100 | 1150 | .015 | .0007 | 9 | 35 |
| 12 | C | S | 450 | $\parallel$ | 50 | 623 | .015 | .0000 | - | - |
| 13 | A | L | 450 | $\parallel$ | 50 | 190 | .005 | .0010 | - | - |
| 14 | A | L | 450 | $\perp$ | 50 | 185 | .007 | .0005 | 20 | 18 |
| 15 | B | M | 450 | $\parallel$ | 50 | 598 | .005 | .0010 | 16 | 50 |
| 16 | B | M | 450 | $\perp$ | 50 | 555 | .003 | .0003 | 8 | 9 |
| 17 | C | S | 450 | $\parallel$ | 20 | 160 | .003 | .0003 | 16 | 50 |
| 18 | C | L | 300 | $\perp$ | 25 | 703 | .001 | .0002 | 16 | 25 |

ABRASIVE FLOW MACHINING - Continued

2. AFM can readily make major changes in surface geometry when removing a significant depth of material. It was, therefore, concluded that the probability of successful application to blisks and the impeller would be substantially greater if final contour milled surfaces have smooth textures which require removal of a much smaller depth of material than rough textures, to achieve the final surface finish.

3. Increased media viscosity gives improved results over the range tested.

4. Increased grit size gives improved results over the range tested.

5. A gap of 1/4 inch is more effective than a gap of 1/2 inch.

6. Flow perpendicular to milled surface waves is considerably more effective than flow parallel to the waves.

7. Lower pressure is more effective than higher pressure for the particular conditions used in these tests. The increased time which occurs with low pressure is not as significant as the increase in effectiveness.

8. Tool design must provide for restrictor wear, by employing lost cost, replaceable restrictor parts.

9. The ideal tooling concept would provide radial flow of the media, so that flow would be perpendicular to milled surface waves; this would increase the probability of successful application of AFM to blisk final surface finishing.

10. Pressures required for AFM were expected to cause high forces to be applied to airfoil surface areas; means would have to be found for applying equal forces to each side of an airfoil as it is finished by AFM, or for supporting one side while the other side is finished.

Similar test results were obtained, and conclusions drawn, from AFM tests performed at Extrude Hone Corp. However, the equipment used by this firm is designed for pressures up to 1750 psi, as opposed to pressures of up to 500 psi used in the Dynetics equipment. It was concluded that higher pressures might be useable where part strength is high, as in the case of the impeller, but lower pressures would be desirable with blisks for the opposite reason.

Further tests were subsequently performed at Dynetics to determine the depth of material which must be removed to improve milled surfaces to meet the 32 microinch AA surface texture required for blisk airfoils. The results showed that surfaces generated with 0.040-inch downfeed require 0.001-inch of material removed to obtain the required texture; 0.020-inch downfeed required 0.0005 inch; and 0.010-inch downfeed required 0.0002-inch to be removed.

Tests were also made to determine the optimum gap width between the test block surface and the AFM tool restrictor surface. The results showed that with a gap of 0.150 inch at the narrowest point and 0.250 inch at the widest point, up to 50% greater depth of material was removed at the narrowest location in the gap. With a 0.450-to 0.550-inch gap, 30% more material was removed.

ABRASIVE FLOW MACHINING - Continued

AFM Tests on Simulated Blisks

A test tool, based on the concept shown in Figure 103 (pg 196), was built for AFM test on simulated Stage 1 blisk airfoils produced from J85 compressor blades, which are forged from AM355 material. It will be noted that the tool allows the abrasive media to flow across the blade surface in either an axial or radial direction.

Tests were conducted with axial flow to determine the effect of AFM on blade thickness, edge contours and chord, while improving surface finish from 90 to 32 microinch AA, using size 20 silicon carbide grit. The results indicated that:

1. The maximum chord reductions occured at the thinnest airfoil section.

2. The maximum chord reduction was 0.007 inch with about 0.002-inch depth of material removed from each side of the airfoil.

3. The edge contours resulting from AFM were sharper than they were before AFM. See Figure 104 (pg 197) for examples.

4. The resulting surface roughness after AFM was 30-microinch AA.

5. Abrasive Flow Machining, with the media flowing axially, was the most promising finishing process, and it was concluded that it should be investigated further.

It was expected that, ultimately, the final edge contour would be dependent on the starting contour and the total depth of material removed. Edge contour requirements are stringent, as indicated in Figure 105 (pg 198).

AFM tests were also conducted on the simulated Stage 1 blisk airfoils to investigate the effect of media flow in a radial direction over the airfoil surface. Surface roughness was found to vary widely over the airfoil surfaces; it significantly exceeded the design requirement near the airfoil tips. In view of these results, it was concluded that axial AFM development should be continued with airfoils identical to Stage 1 blisk design and that work should be discontinued on radial AFM.

Additional axial AFM test were conducted on simulated Stage 1 blisk airfoils to compare the surface roughness produced by media containing aluminum oxide abrasive with that produced by media containing silicon carbide abrasive of equal viscosity, quantity, and grit sizes. The tests showed that aluminum oxide media produced a lower surface roughness (25- to 35-microinch AA) than did the silicon carbide media (25- to 55-microinch AA).

Stage 1 Blisk Airfoil AFM Tooling

A tool concept was developed for the investigation of axial AFM of Stage 1 blisk airfoils. The concept is shown in Figure 106 (pg 199). It will be noted that the concept allows the abrasive media to flow along both sides of the test airfoil, one side of each of the two airfoils adjacent to the test airfoil, the adjacent platform areas, and a restrictor ring at the tips of the airfoils.

ABRASIVE FLOW MACHINING - Continued

Stage 1 Blisk Airfoil AFM Tooling - Continued

Figures 107-109 (pgs 200-202) show views of the actual AFM test tool with a Stage 1 blisk mounted in it. Cast epoxy resin inserts were provided for supporting airfoils adjacent to the center test airfoil, as shown in Figures 108-109.

AFM Tests on Stage 1 Blisks

The abrasive used in AFM tests on Stage 1 blisks was Dynetics media D070-20A(61)-36A(75)-700A(40). It had been observed that this abrasive improved the surface roughness on simulated blisk airfoils from as high as 85-microinch AA to better than 32-microinch AA, in 120 cycles at 150 psi, in less than 20 minutes. The depth of material removed, under these conditions, was between 0.0005 and 0.001 inch.

An airfoil contour tracing system, described in Inspection Process Development, section (pgs 217-220), after AFM.

In addition, a leading edge contour inspection system, also described in the Inspection Process Development section, was used for recording airfoil edge contours before and after AFM.

The first tests involving the use of the AFM tool, were performed on a Stage 1 scrap production blisk with finished surfaces and edge contours. The results of these tests are shown in Table 27 (pg 173). The leading edge contours, produced by AFM on one-half of the airfoils tested, met design requirements. Surface roughness was approximately 15-microinch AA, remaining the same as before AFM. The tests also showed that cycle time changes can be readily held to acceptable limits by control of temperature and pressure. It should be mentioned that, based on previous investigations, the minimum temperature of 90°F was appropriate since cycle times become very long at lower temperatures. The maximum temperature of 120°F was chosen for safe and convenient handling of parts by AFM machine operators. Also, previous investigations indicated that pressures of 150 to 250 psi resulted in the lowest variation in depth of material removed and produced as good a surface texture as pressures above this range.

Additional AFM tests were next performed on 10 Stage 1 blisk airfoils, nine of which were on scrap production blisks and one was milled on the New England 5-axis, 4-spindle NC milling machine. Among other analyses, the resultant data was evaluated to determine the influence of AFM on airfoil geometry.

The following results were obtained, and conclusions drawn, from the above AFM tests:

1. A relatively low media pressure of approximately 150 psi is optimum for maintaining airfoil geometry within design limits.

2. The maximum number of AFM cycles is approximately 120, for minimum effect on airfoil geometry.

3. All media temperatures between 95°F and 125°F are equally suitable for obtaining the required geometry.

TABLE 27

STAGE 1 BLISK AIRFOIL AFM TEST DATA

| Blade No. | Pressure (psi) | Total AFM Cycles 0 | 10 | 20 | 30 | 40 | 50 | 60 | 75 | 90 | 100 | 120 | 150 | 200 | 240 | Avg Cycle Time and Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Time in Minutes (Top No.) and Temperature in °F (Bottom No.)** | | | | | | | | | | | | | | |
| | | 0 | 2.1 | 4.1 | - | - | 9.3 | - | 13.4 | - | 16.9 | 19.7 | | | | .16 |
| 3 | 150 | 123 | 104 | 103 | - | - | 102 | - | 103 | - | 107 | 108 | | | | 105 |
| | | 0 | 0.6 | 1.2 | - | - | 3.1 | - | 4.6 | - | - | 7.1 | | | | .06 |
| 5 | 250 | 90 | 106 | 105 | - | - | 112 | - | 112 | - | - | 116 | | | | 109 |
| | | 0 | 2.4 | 4.2 | 5.5 | 7.0 | 8.4 | 9.7 | - | 13.6 | 14.6 | 17.0 | | | | .14 |
| 7 | 150 | 119 | 115 | 116 | 118 | 120 | 122 | 122 | 123 | 124 | 124 | 124 | | | | 122 |
| | | 0 | 2.0 | 3.6 | 4.5 | 5.5 | 6.5 | 7.6 | | | | | | | | .13 |
| 9 | 150 | 119 | 115 | 114 | 118 | 120 | 122 | 124 | | | | | | | | .119 |
| | | 0 | 2.1 | 3.6 | 4.7 | 5.8 | 6.9 | 8.0 | 9.3 | 10.8 | 11.6 | 13.8 | 16.8 | 21.7 | 25.6 | .11 |
| 11 | 150 | 119 | 114 | 115 | 116 | 119 | 121 | 123 | 125* | 120 | 122 | 123 | 123 | 124* | 122 | 121 |
| | | 0 | 4.8 | 8.3 | 10.1 | 13.7 | 15.9 | 18.3 | 22.1 | 25.5 | 27.5 | 32.4 | | | | .27 |
| 13 | 150 | 90 | 88 | 89 | 89 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | | | | 90 |
| | | 0 | 1.4 | 2.3 | 3.1 | 3.9 | 4.7 | 5.5 | 6.5 | 7.5 | 8.1 | 9.5 | | | | .08 |
| 15 | 150 | 90 | 83 | 96 | 100 | 102* | 100* | 100* | 100* | 100* | 100* | 100 | | | | 98 |
| | | 0 | 1.3 | 2.1 | 2.8 | 3.6 | 4.4 | 5.1 | | | | | | | | .08 |
| 17 | 250 | 105 | 102 | 103 | 104 | 105 | 105 | 105 | | | | | | | | 104 |
| | | 0 | .8 | 1.6 | 2.1 | 2.6 | 3.2 | 3.7 | 4.6 | 5.3 | 5.8 | 6.8 | | | | .06 |
| 19 | 250 | 120 | 114 | 116 | 120 | 122 | 124* | 124* | 125* | 126* | 124* | 124 | | | | 122 |

**Example 2.1 - Time in minutes
104 - Temperature in °F

Test Conditions:
Media - Dynetics - D070-20A(61)-36A(75)-700A(40)
Test Piece - Scrap Production Stage 1 Blisk

Note:
*Test stopped, media temperature was too high. Test restarted after media cooled to test temperature.

ABRASIVE FLOW MACHINING - Continued

4. On the airfoil produced by the New England machine, surface roughness was improved from 30-60 to 15-20 microinch AA and the leading edge contour was improved from square to one that approximated design requirements.

5. The depth of material removed from one side of an airfoil, under the test conditions shown in Table 28 (pg 175) varied from 0.4 to 1 mil.

6. No evidence was found that airfoils were strained beyond their eleastic limit by forces developed during AFM procedures.

7. Chord length changes produced by AFM were large, indicating a need for further development of the AFM process in this connection.

8. Test results indicated that acceptable airfoil surface texture can be obtained by AFM and that this finishing process can produce airfoil edge contours which are consistently within design limits.

Subsequent AFM tests performed simultaneously on three scrap production Stage 1 blisks, with a modified AFM test tool, showed that the depth of material removed from airfoil surfaces ranged between 0.4 and 0.9 mil with test parameters which previously produced surface roughness well below the design requirement (32 microinches AA).

Additional AFM test were conducted to investigate the relationship between the number of AFM cycles and chord length reduction. At 60 cycles, the maximum chord reduction was near the airfoil tip and was 0.005 inch. The minimum reduction was near the platform and was 0.002 inch. These values are well within the Stage 1 chord design tolerance spread of +0.007 inch an -0.009 inch.

An improved abrasive media, which has characteristics at room temperature similar to those of the original medium, was tested on Stage 1 and 2 blisks. The test results indicated that the improved abrasive media performance at 70°F to 100°F was about the same as that of the original media at temperatures of 90°F to 120°F.

The first complete Stage 1 blisk milled on the 5-axis, 4-spindle development milling machine, was finished with abrasive flow machining, using the production AFM tooling and the production machine. A total of 1192 dimensional and surface texture measurements were made on 10 airfoils and 20 platforms; 95% of these measurements were within design limits. This level of conformance to design was considered to be satisfactory for a complex part, and was judged clearly acceptable for engine testing. Conformance of the contours of the leading edges, which is a particularly important characteristic, was 100% and conformance of overall airfoil contours, another very important characteristic, was essentially 100%.

All airfoils were abrasive flow machined simultaneously. A total of 75 AFM cycles were covered in the process. Measured surface roughness averaged 23 microinches AA. The design requirement of 32-microinch AA was exceeded in only two locations: at one by two microinches and at the other by five microinches. The total AFM cycle time was 35 minutes.

## TABLE 28
## REDUCTION IN THICKNESS BY AFM OF SCRAP PRODUCTION STAGE 1 BLISK AIRFOILS

| Blisk No. | Airfoil No. | Section | Media Pressure (psi) | Media Temp (°F) | AFM Time (min) | Cycles | Reduction in Airfoil Thickness at Seven Locations — Leading Edge: L | M | N | O | P | Q | R (Trailing Edge) | Average (mils) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 104 | 3 | BB | 150 | 90 | 33 | 120 | 1.0 | .8 | .8 | .8 | .9 | .6 | 1.5 | .9 |
| | | DD | | | | | 1.0 | .7 | .5 | .8 | 1.0 | 1.2 | 1.8 | 1.0 |
| | | HH | | | | | 1.3 | 1.1 | 1.4 | 1.1 | .7 | .8 | 1.7 | 1.2 |
| | | | | | | Average | 1.1 | .9 | .9 | .9 | .9 | .9 | 1.7 | 1.0 |
| 104 | 5 | BB | 150 | 105 | 21 | 120 | 1.8 | .9 | 1.0 | .6 | .7 | 1.2 | 1.6 | 1.1 |
| | | HH | | | | | 1.3 | 1.3 | 1.3 | 1.8 | 1.8 | 1.5 | 1.4 | 1.5 |
| | | | | | | Average | 1.5 | 1.1 | 1.2 | 1.2 | 1.2 | 1.3 | 1.5 | 1.3 |
| 104 | 7 | BB | 150 | 125 | 17 | 120 | 1.2 | 1.0 | 1.0 | .9 | .4 | .4 | 1.1 | .9 |
| | | DD | | | | | 1.4 | .8 | .8 | .7 | .9 | .7 | 2.1 | 1.1 |
| | | HH | | | | | .5 | .6 | .4 | .6 | .8 | 1.0 | .6 | .6 |
| | | | | | | Average | 1.0 | .8 | .7 | .8 | .7 | .7 | 1.3 | .9 |
| 424 | 5 | BB | 150 | 125 | 9 | 60 | -.6 | -.1 | .3 | .4 | .6 | 1.2 | 2.8 | .7 |
| | | DD | | | | | x | .1 | .6 | .5 | 1.9 | 1.6 | 2.3 | 1.0 |
| | | HH | | | | | .6 | .4 | .4 | .7 | .7 | 1.3 | 1.1 | .7 |
| | | | | | | Average | 0 | .1 | .4 | .5 | 1.9 | 1.4 | 1.4 | .8 |
| 424 | 7 | BB | 150 | 125 | 29 | 240 | 1.6 | 1.2 | 2.3 | 1.9 | 3.0 | 3.1 | 4.0 | 2.5 |
| | | DD | | | | | 2.9 | 2.7 | 2.8 | 3.2 | 3.3 | 2.9 | 4.7 | 3.2 |
| | | HH | | | | | 2.0 | 1.3 | 2.1 | 2.6 | 2.8 | 2.8 | 3.6 | 2.6 |
| | | | | | | Average | 2.2 | 1.7 | 2.4 | 2.6 | 3.0 | 2.9 | 4.1 | 2.7 |
| 424 | 13 | BB | 250 | 105 | 6 | 60 | -.7 | -.6 | 2.1 | .4 | .9 | 2.1 | 2.3 | .9 |
| | | DD | | | | | -.2 | .4 | .3 | 1.0 | 2.0 | 2.1 | 2.5 | 1.2 |
| | | | | | | | .1 | .7 | .5 | .6 | .8 | 1.6 | 1.5 | .8 |
| | | | | | | Average | -.3 | .2 | 1.0 | .7 | 1.2 | 1.9 | 2.1 | 1.0 |

## TABLE 28
## REDUCTION IN THICKNESS BY AFM OF SCRAP PRODUCTION STAGE 1 BLISK AIRFOILS

| Blisk No. | Airfoil No. | Section | Media Pressure (psi) | Media Temp (°F) | AFM Time (min) | Cycles | L | M | N | O | P | Q | R | Average (mils) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Reduction in Airfoil Thickness at Seven Locations (Leading Edge → Trailing Edge) | | | | | | | |
| 424 | 15 | BB | 250 | 90 | 10 | 120 | .9 | 1.6 | 2.1 | 2.8 | 2.8 | 3.0 | 3.8 | 2.3 |
| | | | | | | | 1.4 | 1.8 | 1.8 | 2.0 | 2.2 | 2.8 | 3.8 | 2.3 |
| | | | | | | | .5 | .6 | 1.6 | 2.3 | 1.9 | 1.8 | 2.0 | 1.5 |
| | | | | | | Average | .9 | 1.3 | 1.8 | 2.4 | 2.3 | 2.5 | 3.2 | 2.0 |
| 424 | 17 | BB | 250 | 105 | 8 | 120 | .6 | .4 | 1.0 | 1.3 | 2.2 | 3.6 | 4.4 | 1.9 |
| | | | | | | | .9 | .9 | 1.2 | 1.6 | 2.6 | 2.8 | 3.8 | 1.9 |
| | | | | | | Average | .8 | .7 | 1.1 | 1.5 | 2.4 | 3.2 | 4.1 | 1.9 |
| 424 | 19 | BB | 250 | 125 | 8 | 120 | .9 | 1.3 | 1.0 | x | 2.0 | 3.3 | 3.9 | 2.1 |
| | | DD | | | | | 1.3 | 1.3 | 2.4 | 2.2 | 2.6 | 3.2 | 3.9 | 2.3 |
| | | HH | | | | | 0 | .4 | 1.2 | 2.3 | 2.0 | 2.0 | 2.6 | 1.5 |
| | | | | | | Average | .7 | 1.0 | 1.5 | 2.2 | 2.2 | 2.8 | 3.5 | 2.0 |

**NOTES:** Negative signs preceding measurements indicate that material was added rather than removed. This is not possible and is the result of measurement inaccuracy.

Inspection Locations:

L is .10 inches from the leading edge.
R is .10 inches from the trailing edge.
O is at the stacking axis.
M, N, P, Q are equally spaced.

**Media:**

Dynetics D070-20A(61)-36A(73)-700(40)
Test Piece - Scrap Production Stage 1 Blisk

## ABRASIVE FLOW MACHINING - Continued

### AFM Development Tooling and Tests on Stage 2, 3, 4, and 5 Blisks

Upon completion of AFM tests on the Stage 1 blisk, AFM development tooling was designed and produced for the Stage 2, 3, 4, and 5 blisks. Extensive process demonstration tests were then performed on these blisks with satisfactory results. The capability of AFM for surface finishing the airfoils in these blisks was demonstrated using the test parameters developed for Stage 1 blisks. Three airfoils were processed simultaneously; chord lengths, surface roughness, contours and thicknesses of all airfoils were within design limits after AFM.

### Production Tooling For AFM

Following completion of Stage 1 blisk AFM tests, the design of a production AFM machine was generated and a machine capable of surface finishing all blisk stages was fabricated. Adaptors were also designed and built to accommodate all blisk stages. The machine is designed for simultaneous processing of all airfoils in a given blisk. Figure 110 (pg 203) shows the design concept for the Stage 1 blisk production tool.

The production AFM machine was tested by machining 15 Stage 1 blisk airfoils simultaneously, to determine if the effects of AFM on airfoil thickness, chords, and leading edge contours were similar to those obtained when machining only a few airfoils on the development machine. The results showed that the effects of AFM were similar for both machining conditions.

It was observed that a warmup period of one hour was required to bring the abrasive media within the planned operating range of 90°F to 120°F. The media temperature continued to rise when machining Stage 1 blisks. An investigation was therefore conducted to develop a media with equivalent AFM properties but capable of operating over a temperature range of 70°F to 100°F. Subsequent tests with such a media, on Stage 1 and 2 blisks, indicated that its performance was the same as that of the original media.

Tests were performed to determine the restrictor ring diameters needed to obtain the same cycle time for the Stages 3 and 4 blisk when machined individually without a flow director. With a ring diameter of 6.565 inches for Stage 3 and 6.420 inches for Stage 4, the cycle time for each was 35 seconds. The conclusion was drawn that, with the same cycle time, the rate of roughness improvement would be the same for both stages when machined simultaneously.

In the case of the Stages 3 and 4 blisk and the Stage 5 blisk tooling, it was necessary to include media flow directors to obtain acceptable airfoil leading edge contours and roughness. These consisted of rough-milled Stage 1 blisk airfoils made from steel blanks. The arrangement for the Stage 5 blisk is shown in Figure 111 (pg 204). The flow director life was found to be, typically, ten Stage 5 blisks.

## ABRASIVE FLOW MACHINING - Continued

### Production Tooling For AFM - Continued

Later, it was found that, when AFM machining the Stages 3 and 4 blisk simultaneously, the cycle time could be reduced almost 20% when a Stage 3 blisk was used as a flow director in place of a Stage 1 blisk. Subsequent to these tests, a method was devised for reducing the time needed to AFM the Stages 3 and 4 blisk and the Stage 5 blisk by simultaneous processing of two blisks of the same king. This procedure also eliminated the need for media flow directors.

## PRODUCTION AFM MACHINE REQUIREMENTS

Requirements for a production AFM machine were established as part of this development program. They are defined in a specification included as Appendix B.

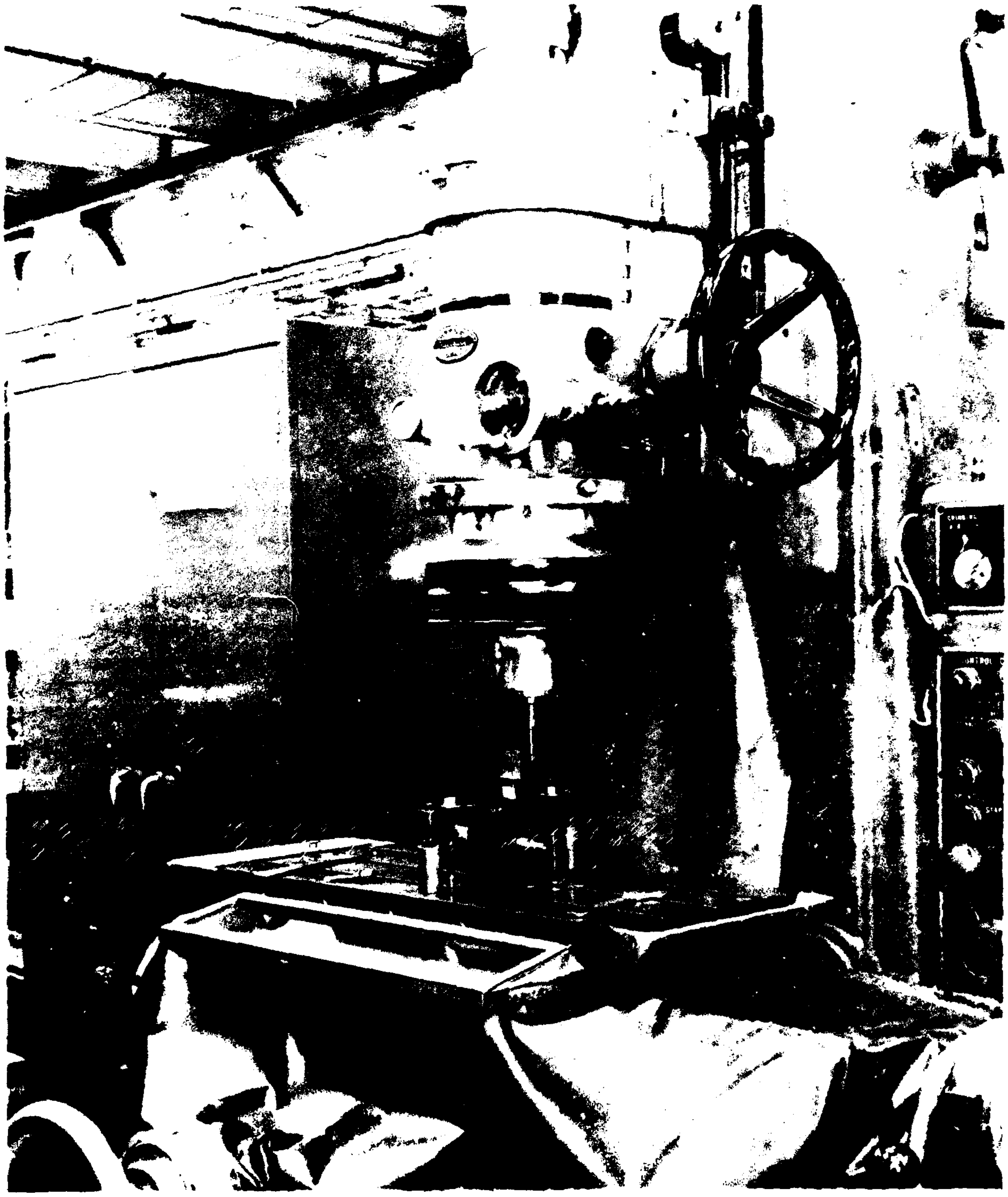


Figure 86. Moore Jig Grinder With Test Piece and Grinding Wheel (Feed Table and Coolant Enclosure Not Shown).

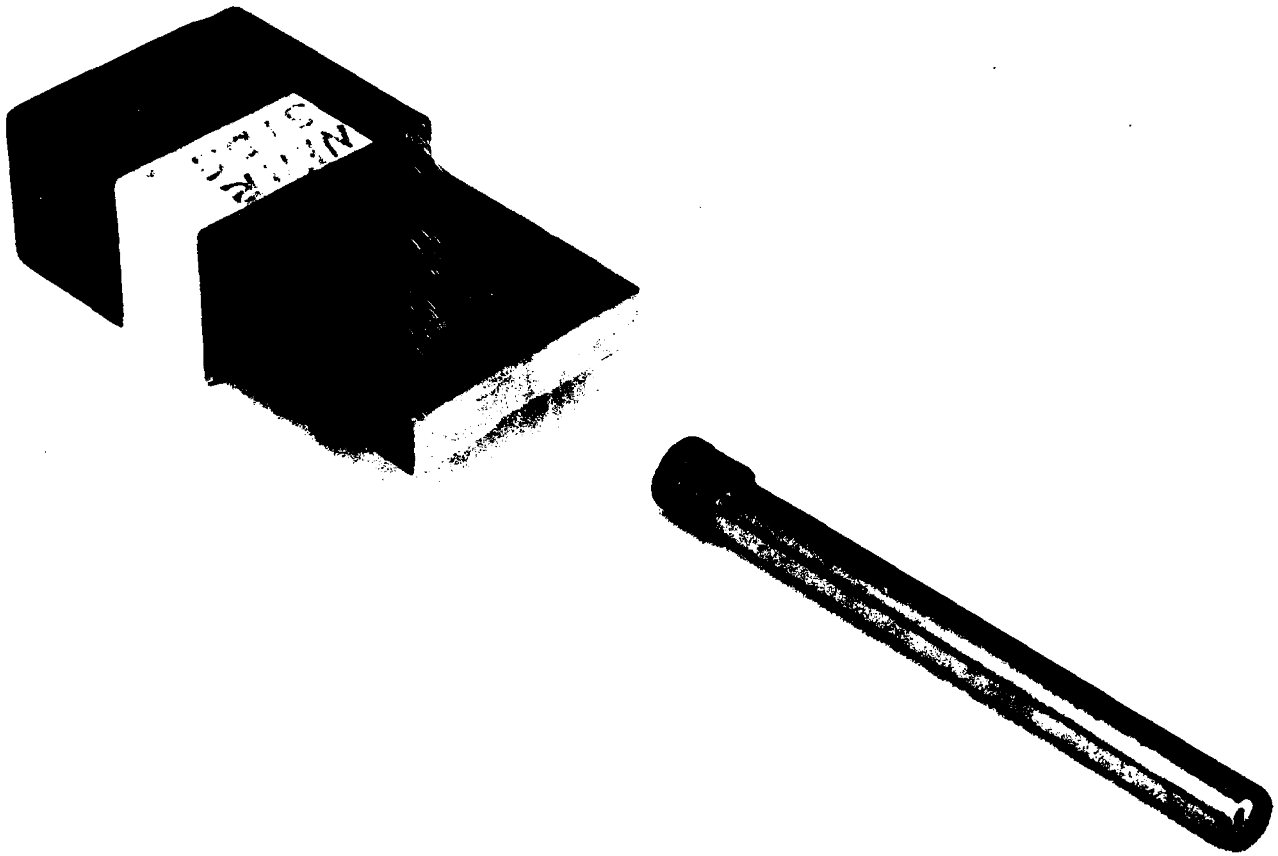


Figure 87. Test Sample of AM355 Material and CBN Borazon Wheel.

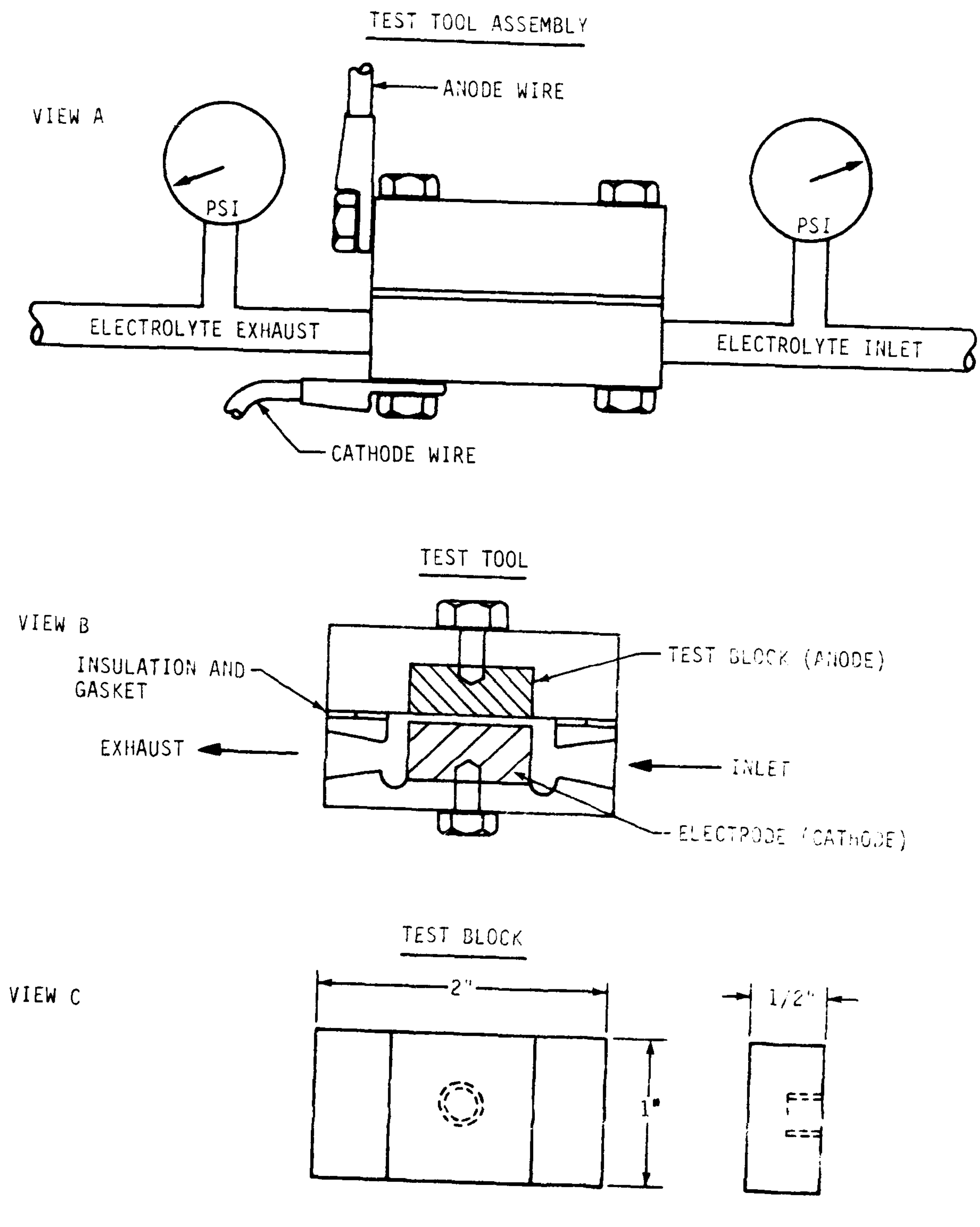



Figure 38. Stationary Electrochemical Machining Test Setup.

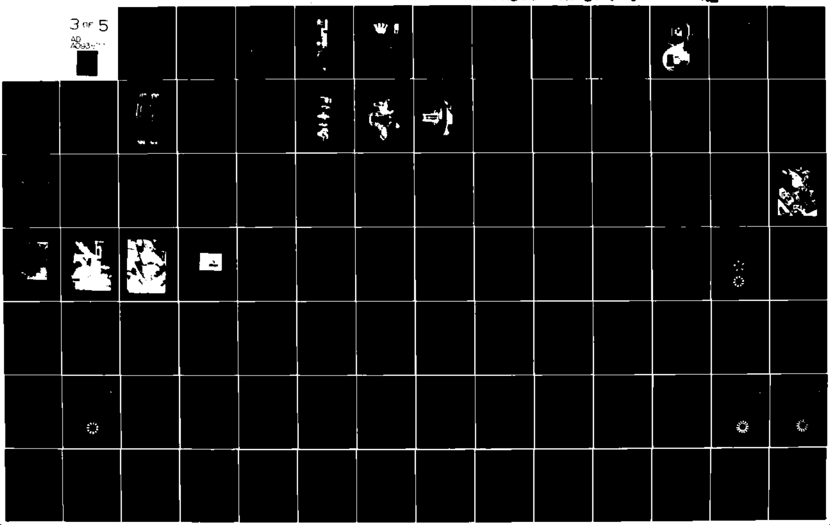
A B C

A) Original test block without SECM processing
B) Center section processed through SECM with cut waves parallel to electrolyte flow.
C) Typical processed test block used in obtaining data on metal removal.

Figure 89. AM355 Test Blocks Used in Stationary Electrochemical Machining [illegible]

AD-A093 877 GENERAL ELECTRIC CO LYNN MA AIRCRAFT ENGINE GROUP F/G 13/8
T700 BLISK AND IMPELLER MANUFACTURING PROCESS DEVELOPMENT PROGR--ETC(U)
NOV 79 W A HUNTER, G A GRIMMER DAAJ01-75-C-0A44
UNCLASSIFIED R80AEG035 USAAVRADCOM-TR-80-F-1 NL

3 OF 5
AD A093



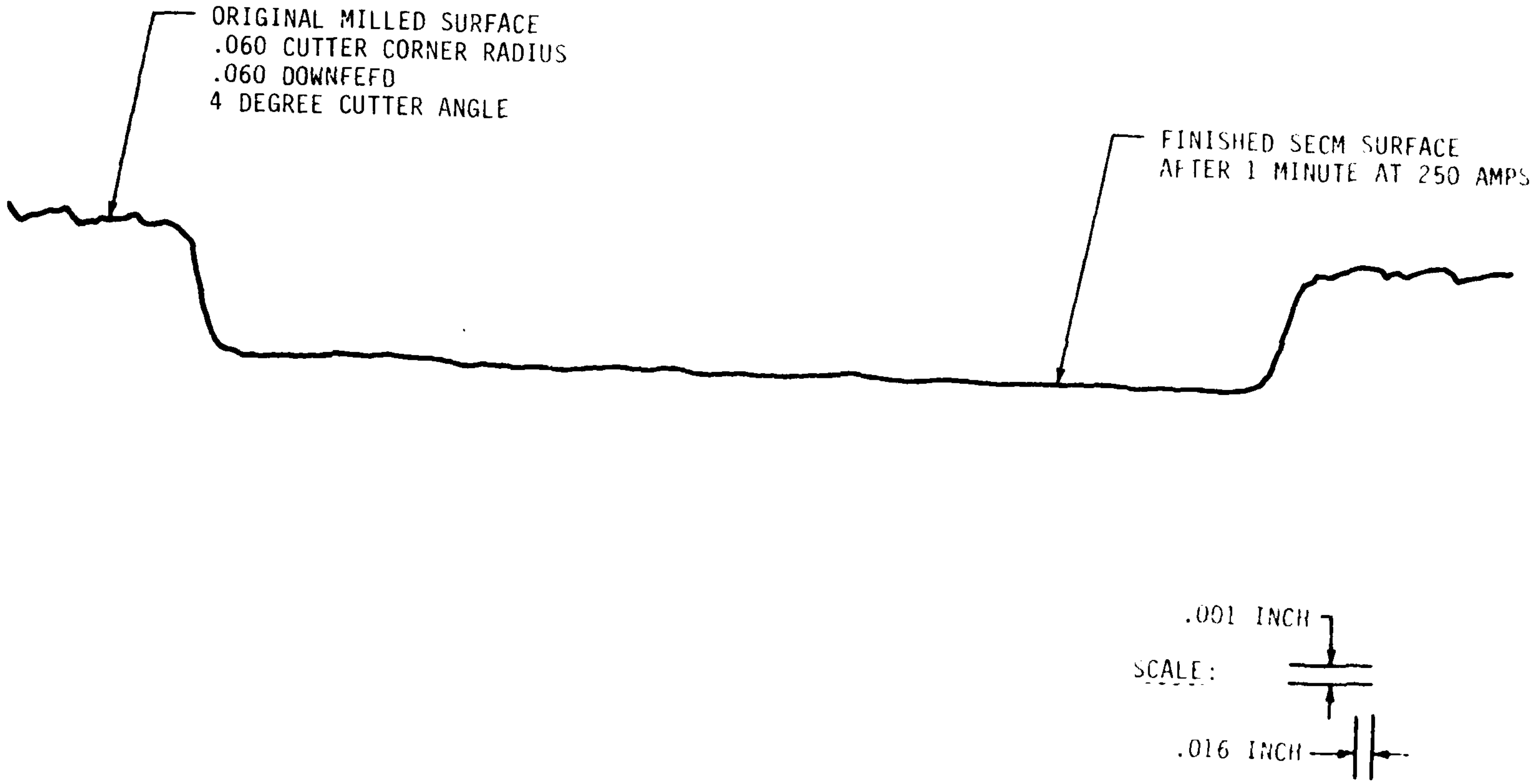



Figure 9[illegible]. Cont[illegible] Profile of AM355 Test Block After SECM

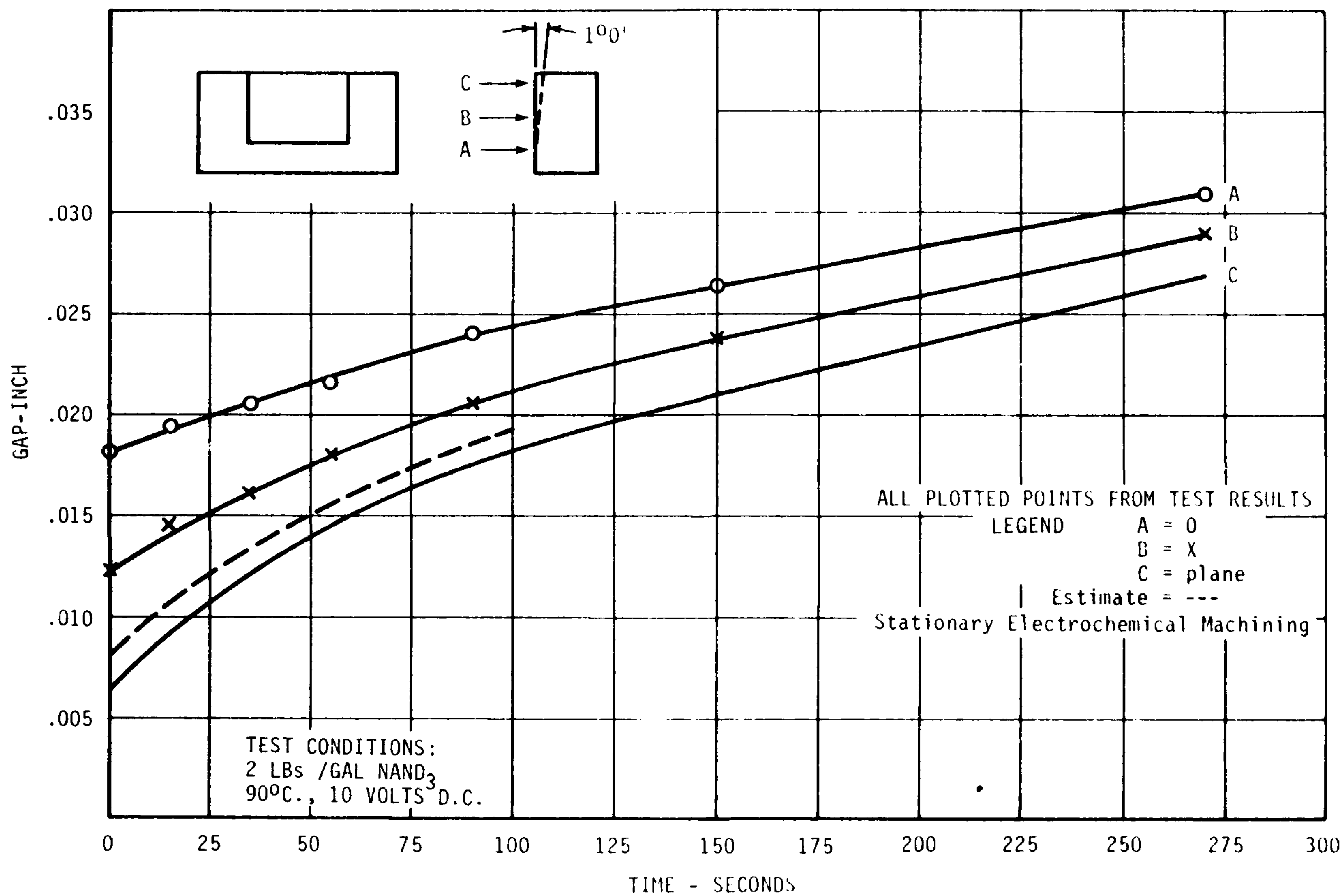



Figure 91. Change in Gap with Time.

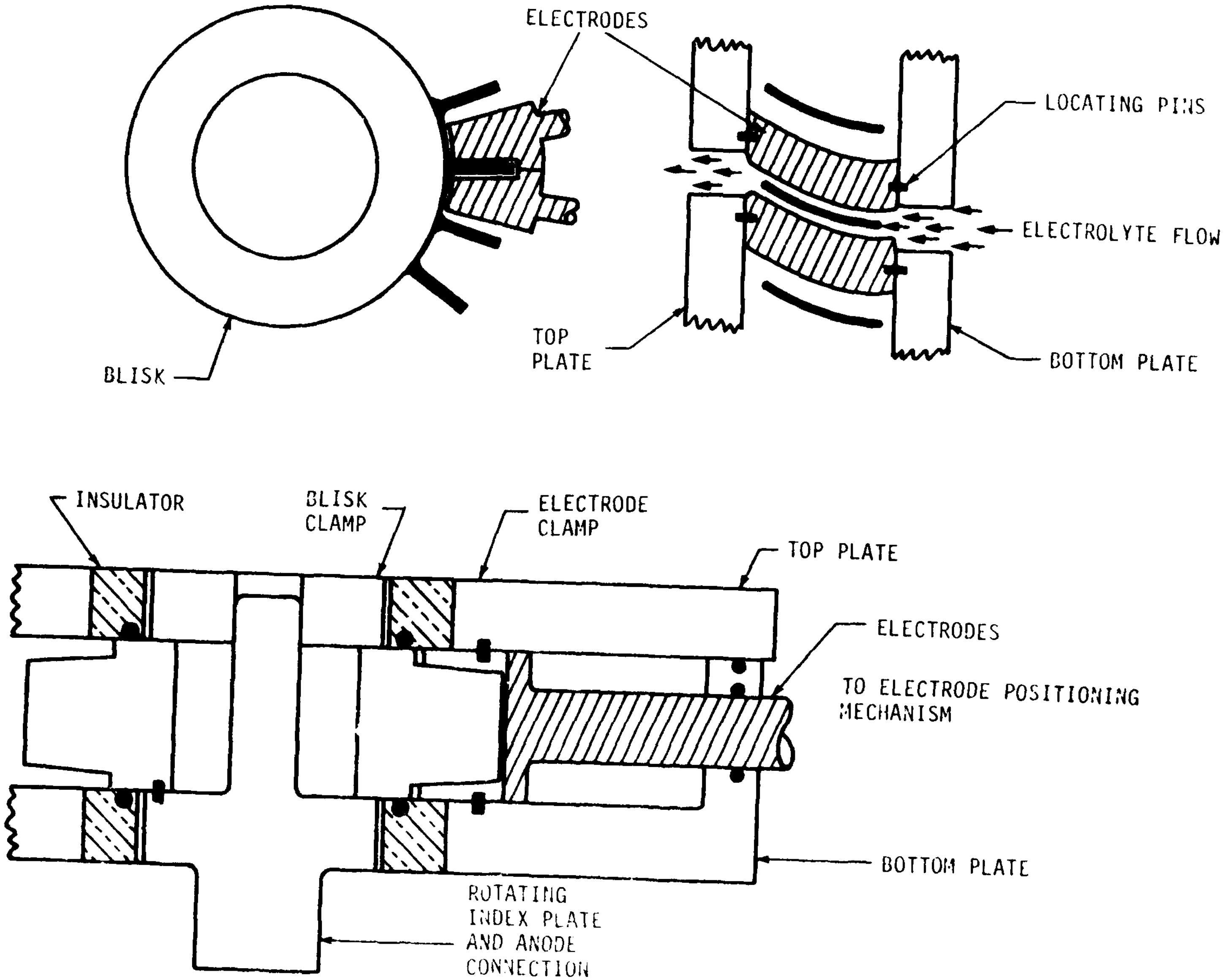



Figure [illegible] Tool Concept.

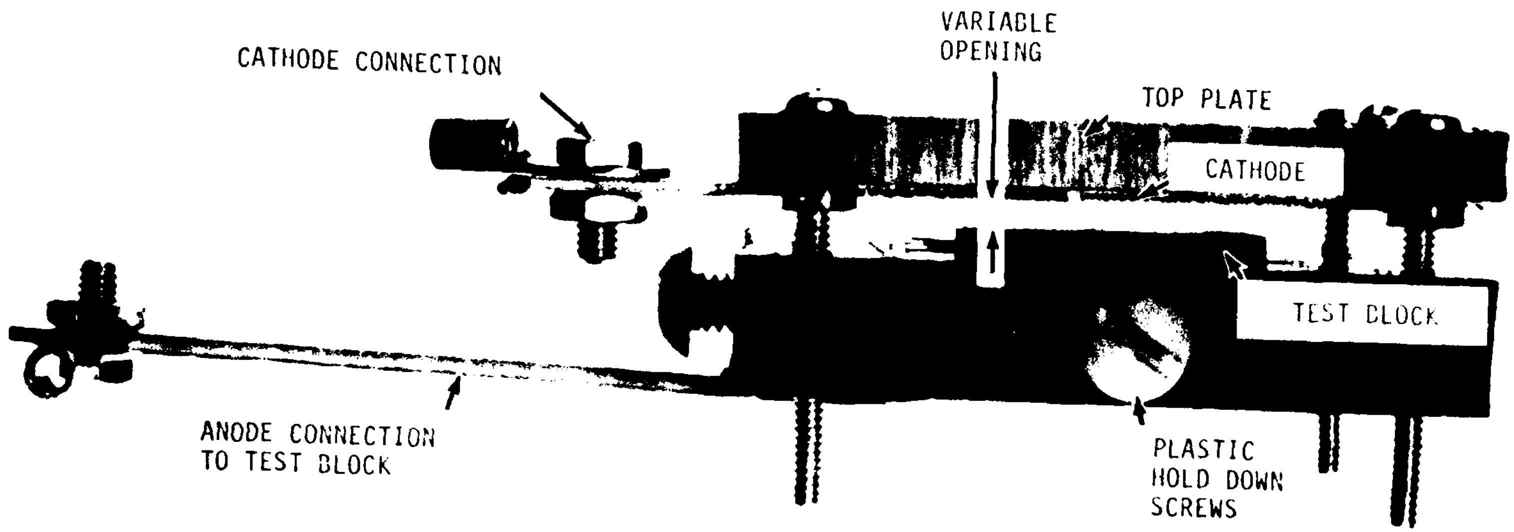
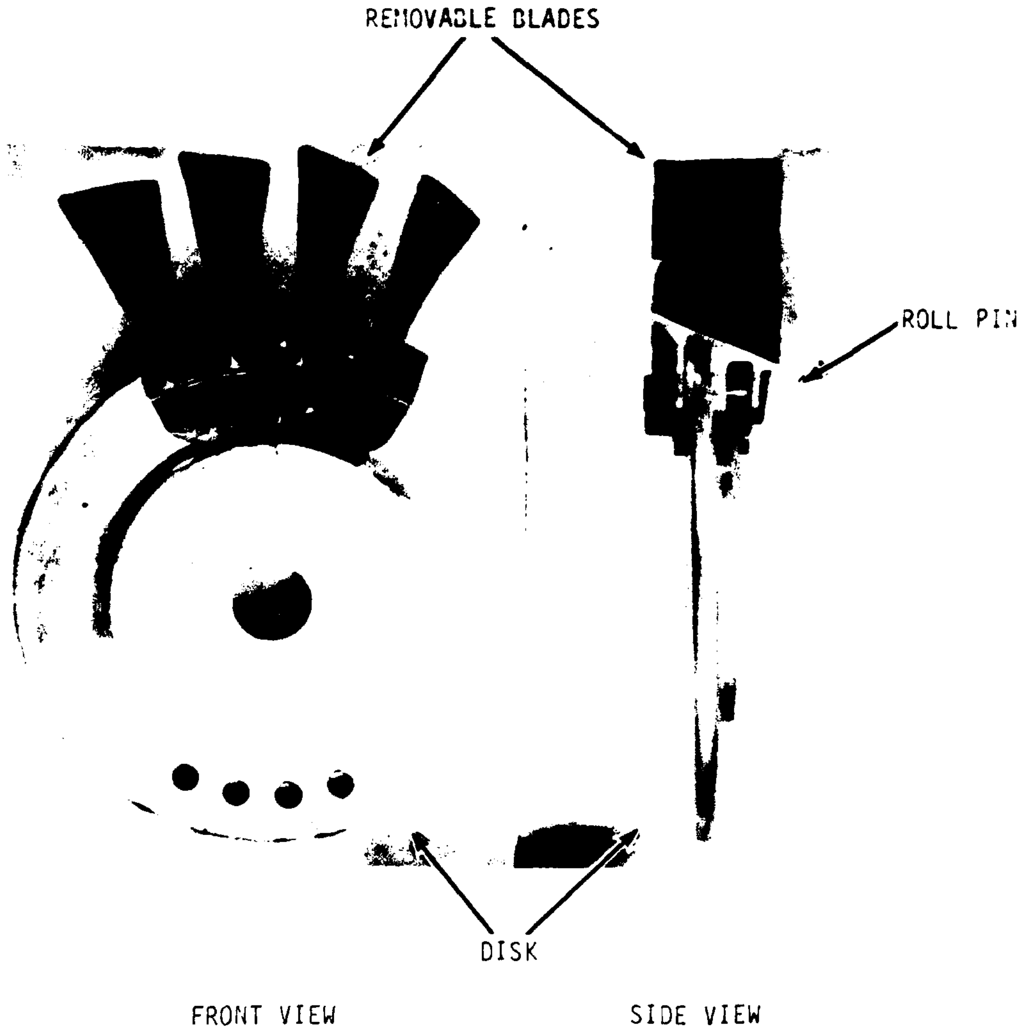
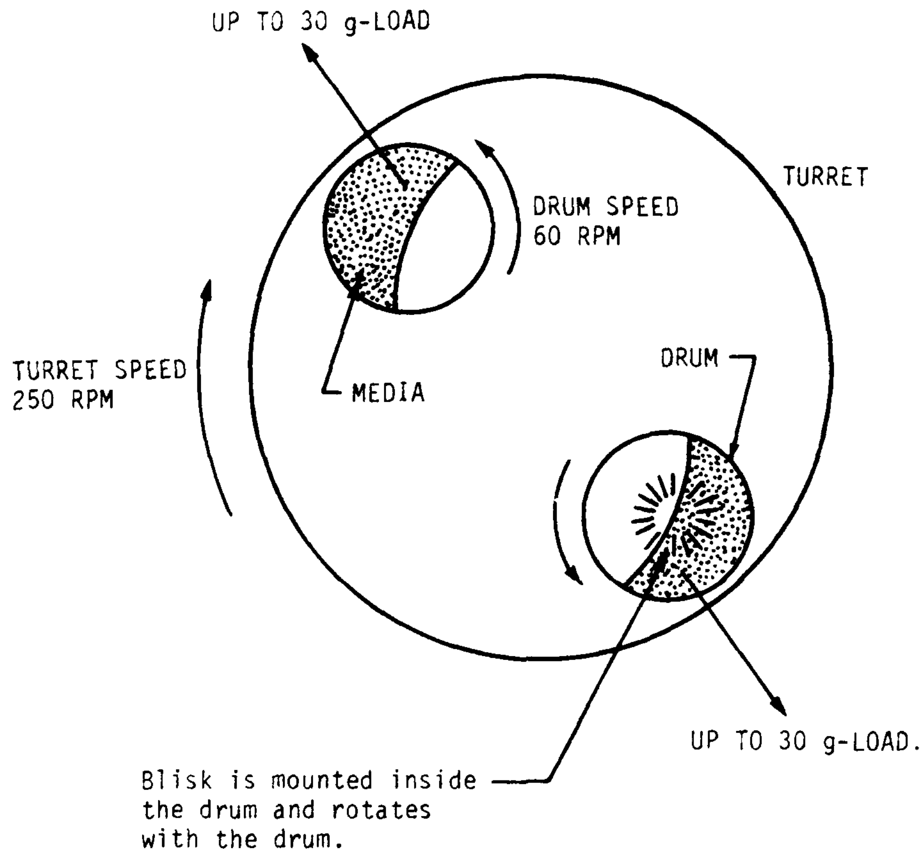



Figure 93. Electropolish Tool and Test Block.



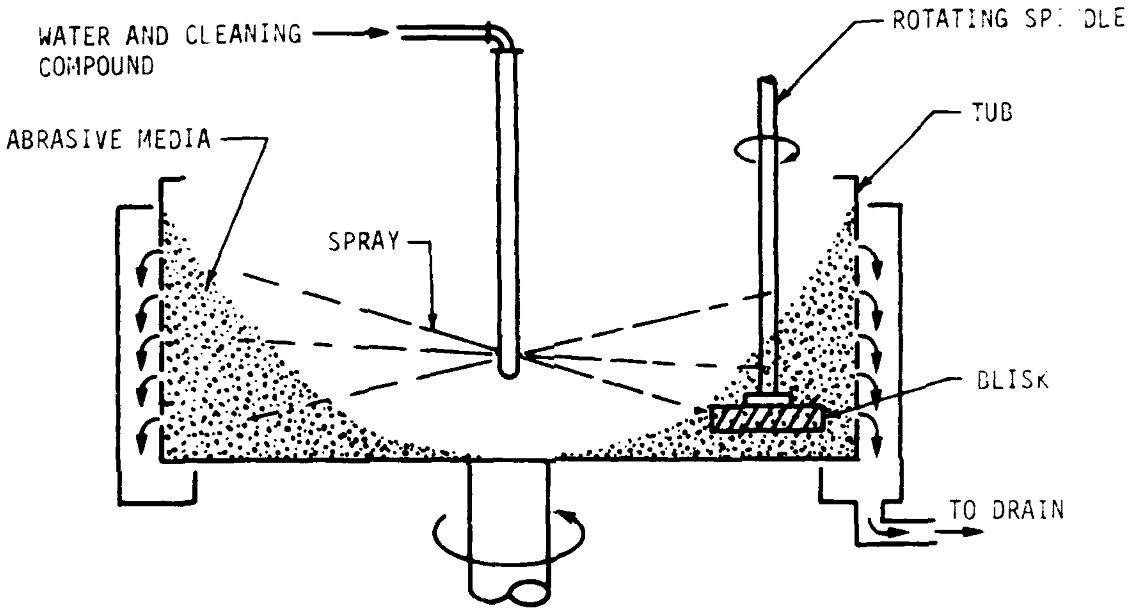

NOTE: The removable test blades consist of the bottom section of J85-Stage 1 blades.

Figure 94. Free Abrasive Machining Test Piece.




The centrifugal barrel finishing equipment is comprised of two drums mounted on the periphery of a turret. The turret is rotated at a high speed in one direction while the drums are rotated at a slower speed in the direction opposite to that of the turret. Drums are loaded with blisks to be finished, media, water and some form of compound. In operation the turret rotation creates a high centrifugal force of up to thirty times gravitational weight. This force compacts the load into a tight mass. Rotation of the drums causes an activity of the load; blisk and media slide against each other, smoothing the milled surface.

Figure 95. Principle of Operation of the Harper Process as Applied to Blisk Airfoil Surface Finish Testing.




- o Tub spins at up to 1200 surface feet per minute.
- o Centrifugal force compacts the abrasive media.
- o Mist spray of water and cleaning compound keeps abrasives free cutting.
- o Slow rotation of the spindle with the part in the abrasive, exposes all surfaces for the more uniform finishing.

Figure 96. ALMCO Spindle Finishing.

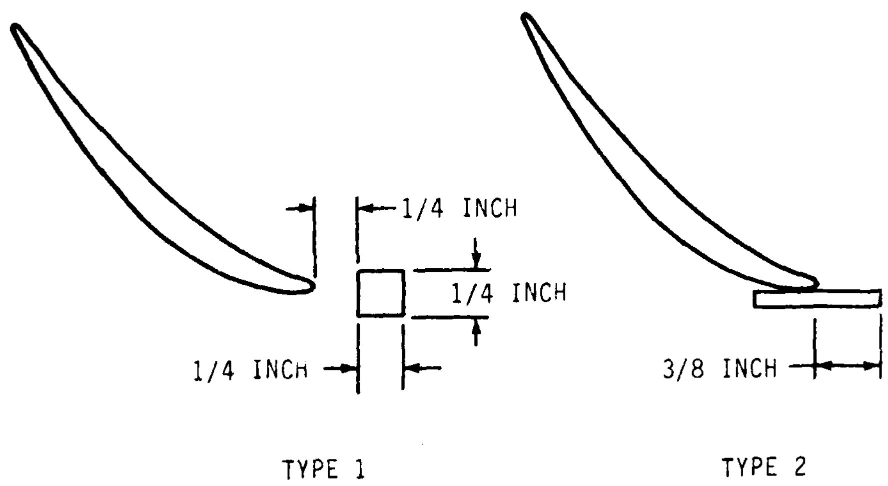
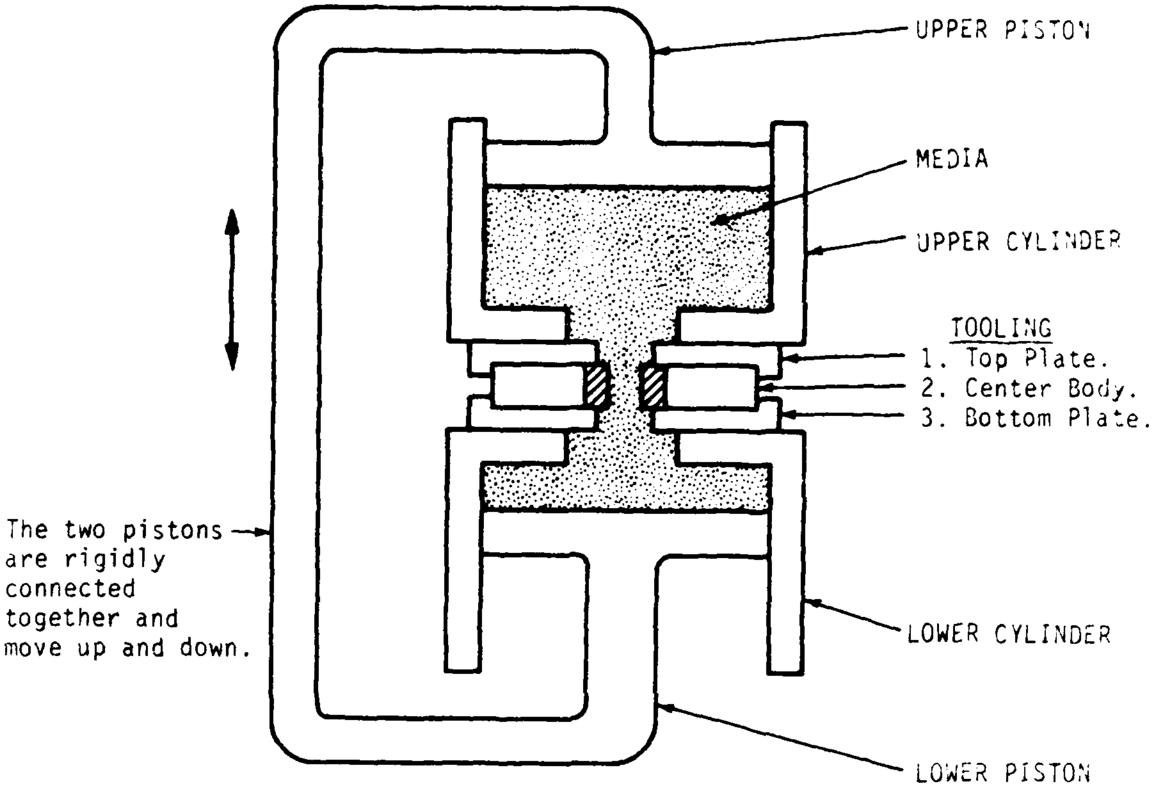
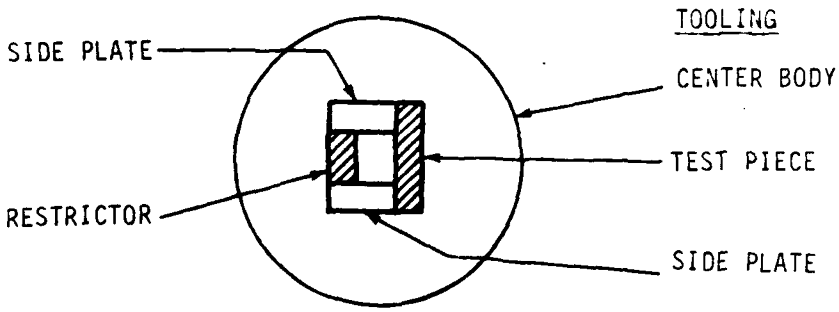



Figure 97. Shields Used to Reduce Removal of Material from Simulated Airfoil Edges in Almco Spindle Finishing Tests.




The AM355 test piece is a 1 in x 2 in x approx 5/8-in thick block. Only the center 1-inch square surface was subjected to abrasive AFM. The remaining 1/2 in on each end was for reference measurements.

Figure 98. Schematic of Abrasive Flow Test Tool and Equipment.

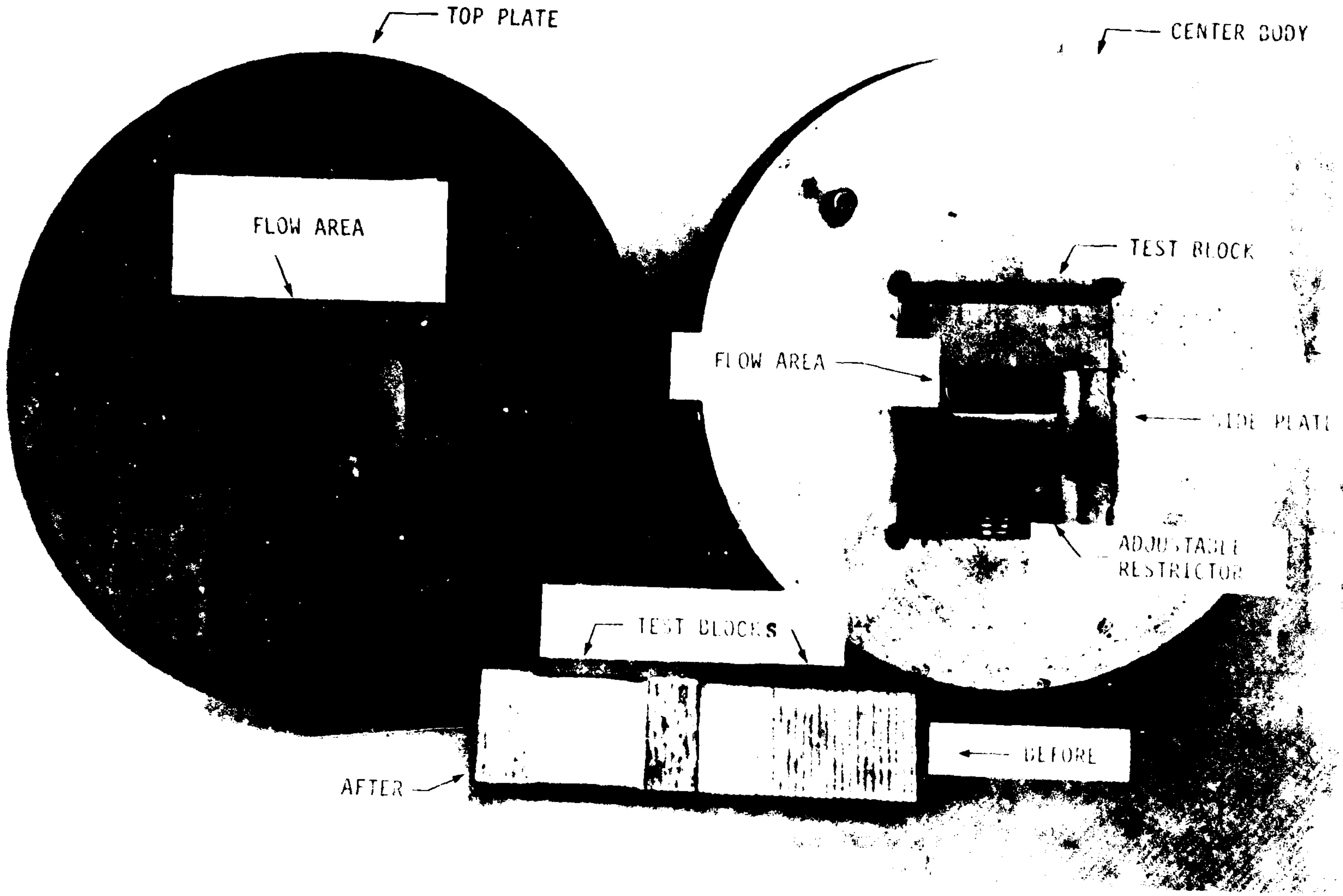



Figure [illegible]. Abrasive Flow Machining [illegible] Tool and Test Block.

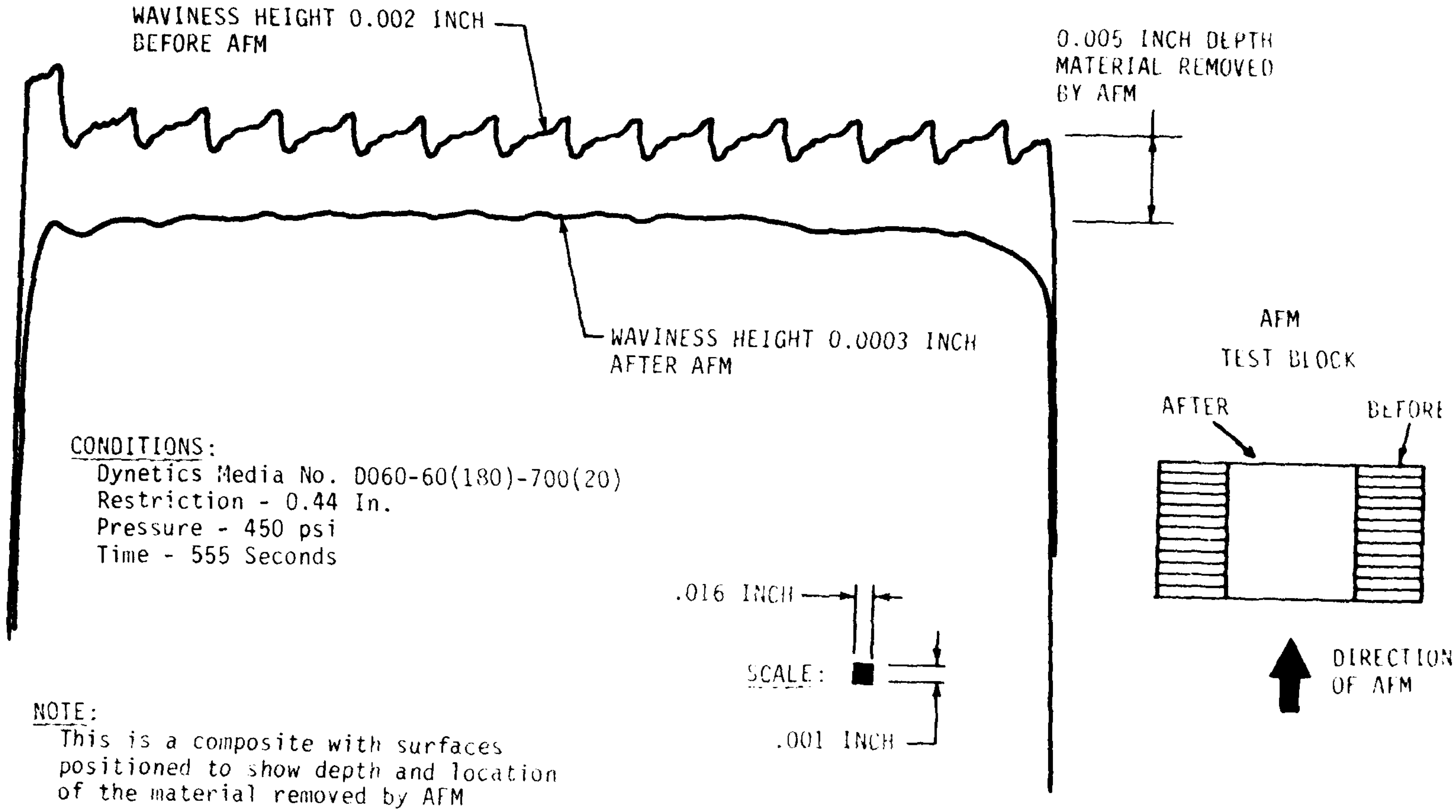
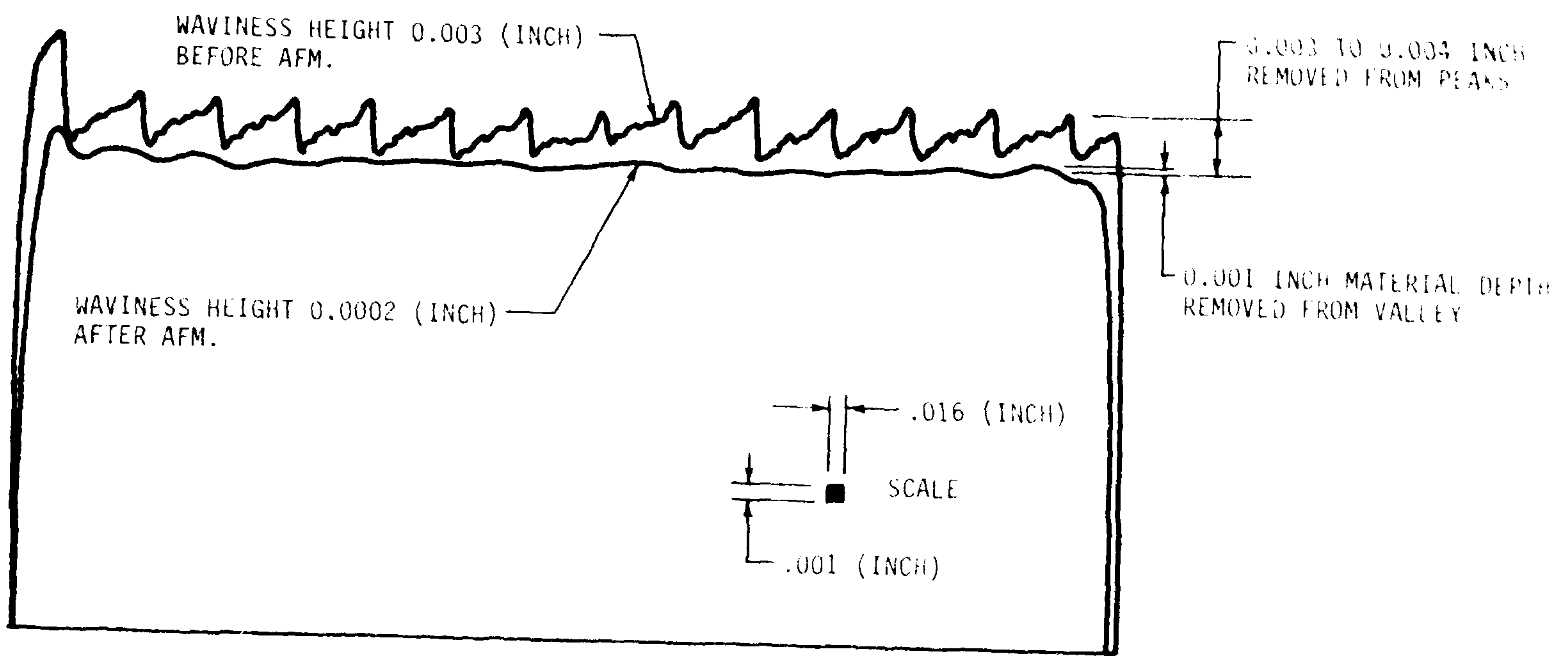



Figure 10[illegible]. Surface Texture Change By Abrasive Flow Machining




NOTE: This is a composite of ContouReader recordings showing depth and location of the material removed by AFM in Test No. 18.

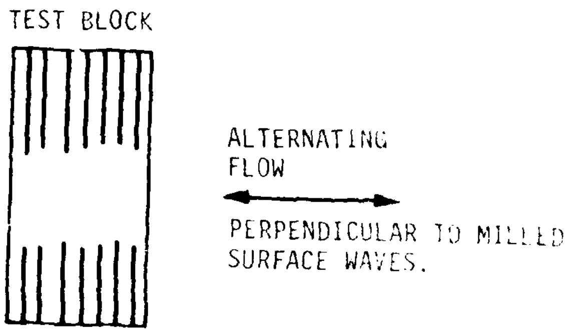
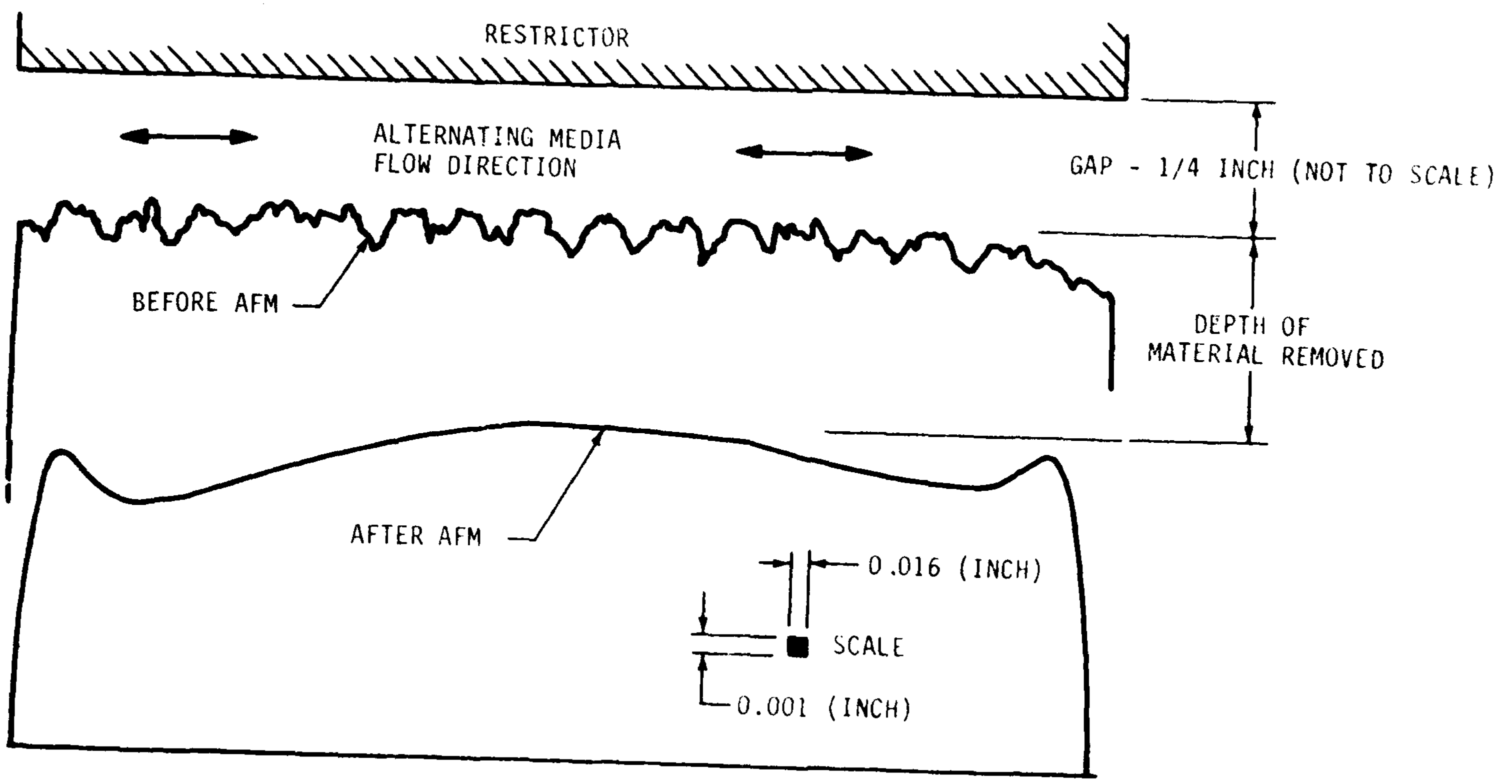



Figure 1[illegible]1. Surface Texture Change by AFM.




NOTE: This is a composite of ContouReader recordings to show typical geometry changes resulting when large depths of material are removed.

NOTE: Left side recording is lower than right side due to misalignment of part with ContouReader.

Figure 102. Geometry Change by AFM.

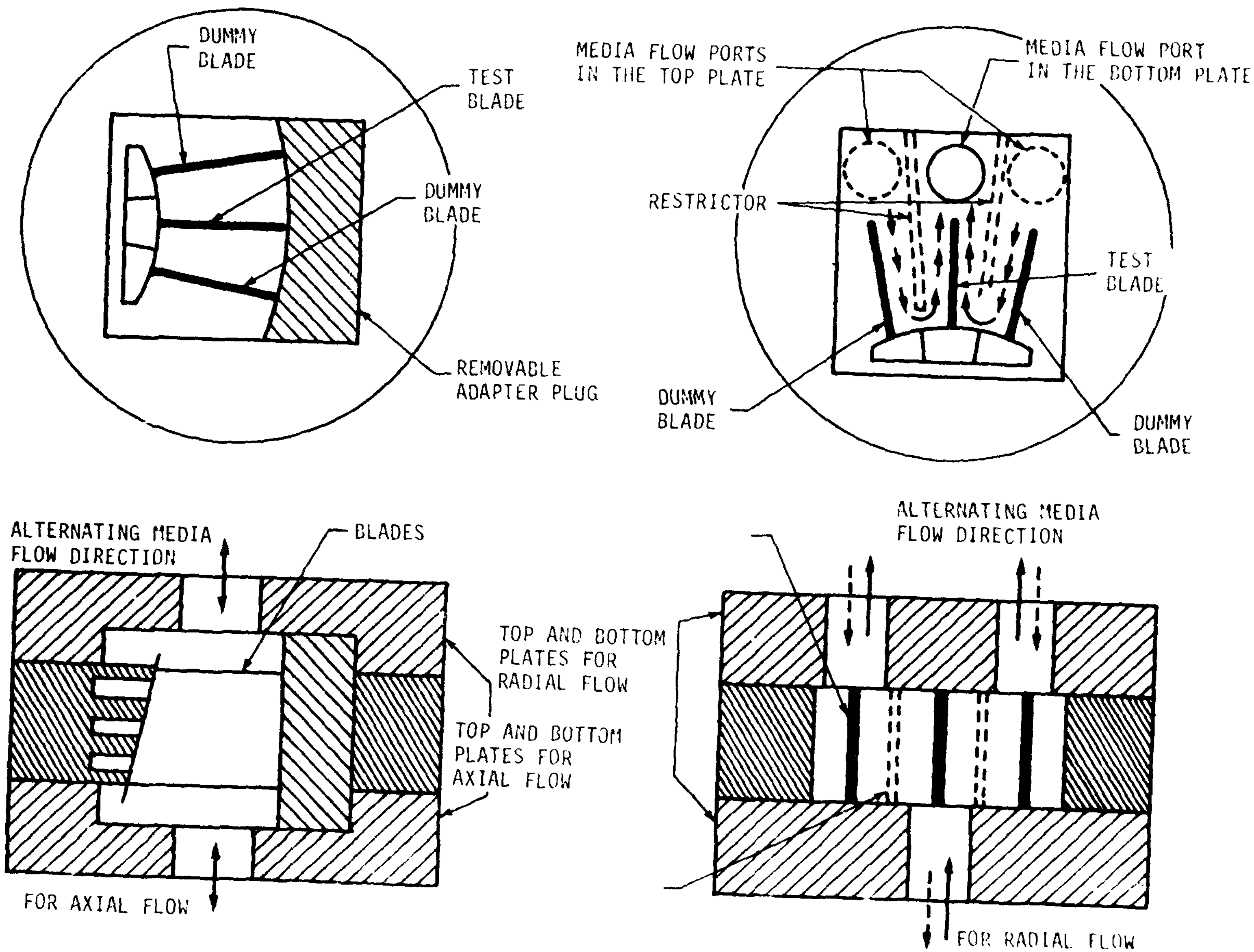
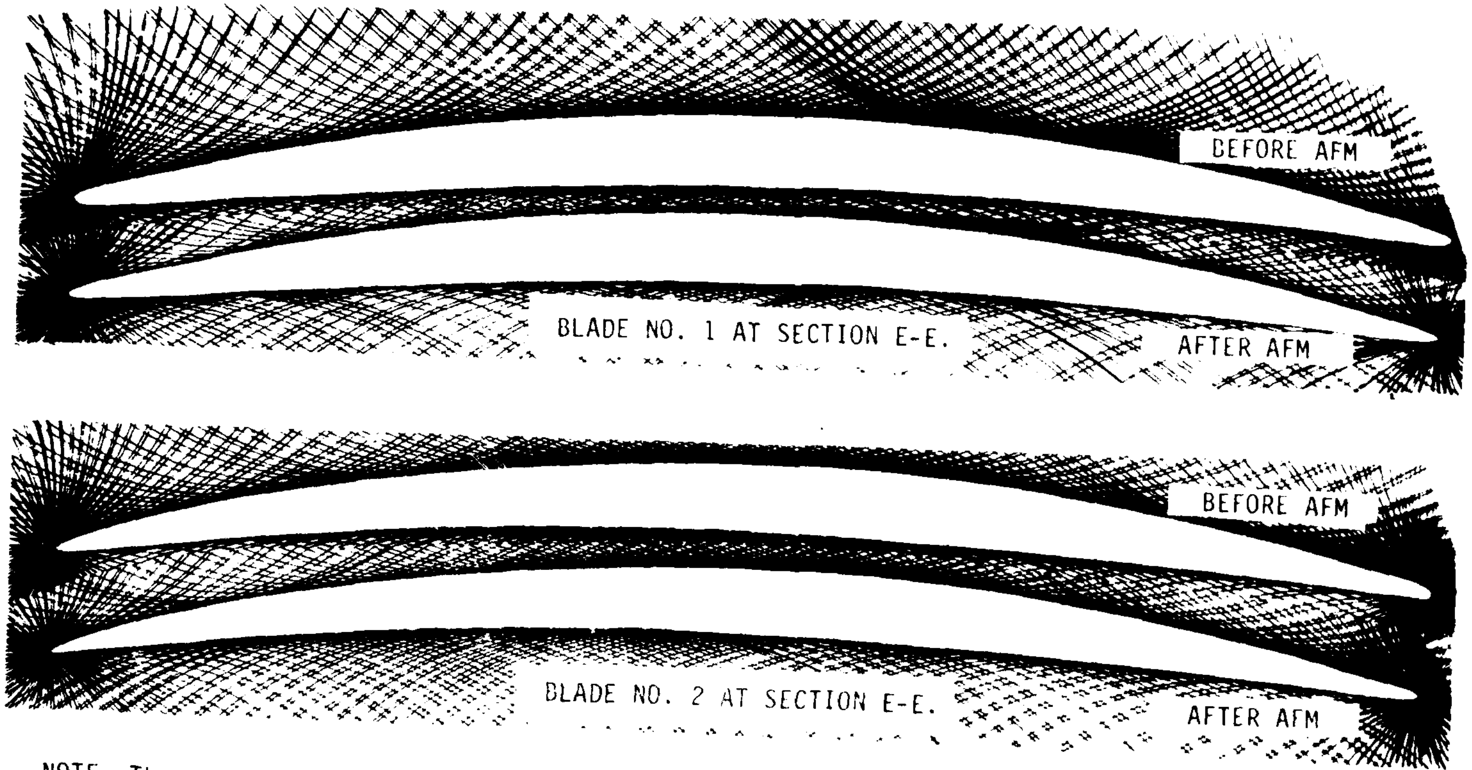


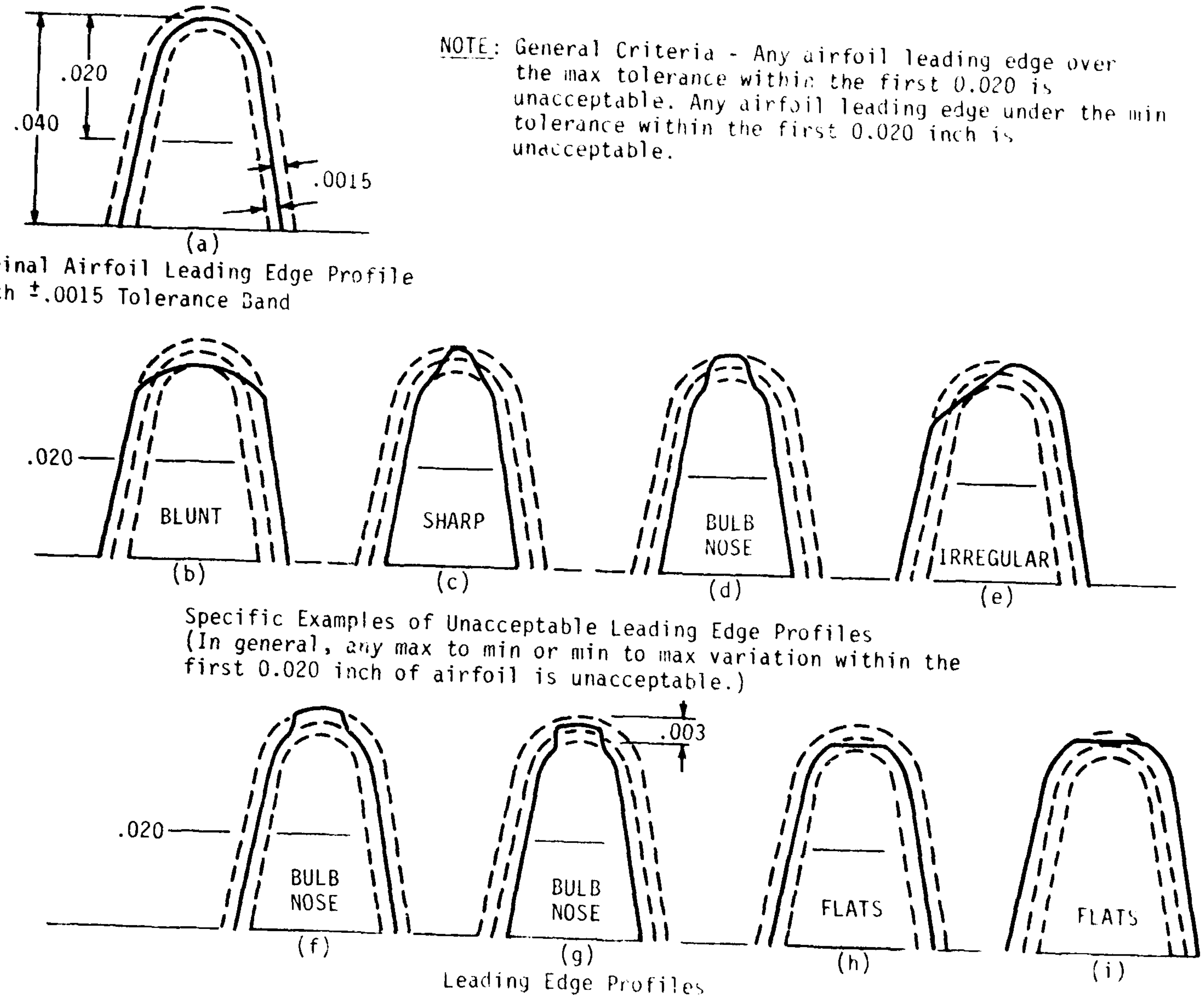

Figure 103. Dual Purpose AFM Test Tool.




NOTE: These sections approx 7X magnification.

Figure 104. Simulated Blade Geometry Changes Produced by AFM.

NOTE: General Criteria - Any airfoil leading edge over the max tolerance within the first 0.020 is unacceptable. Any airfoil leading edge under the min tolerance within the first 0.020 inch is unacceptable.




Examples of Unacceptable Airfoil in Max to Nominal and Nominal to Min Variation (Within the first 0.003 inch of airfoil width of tolerance).

Figure 105. Airfoil Leading Edge Contour Specification Illustration.

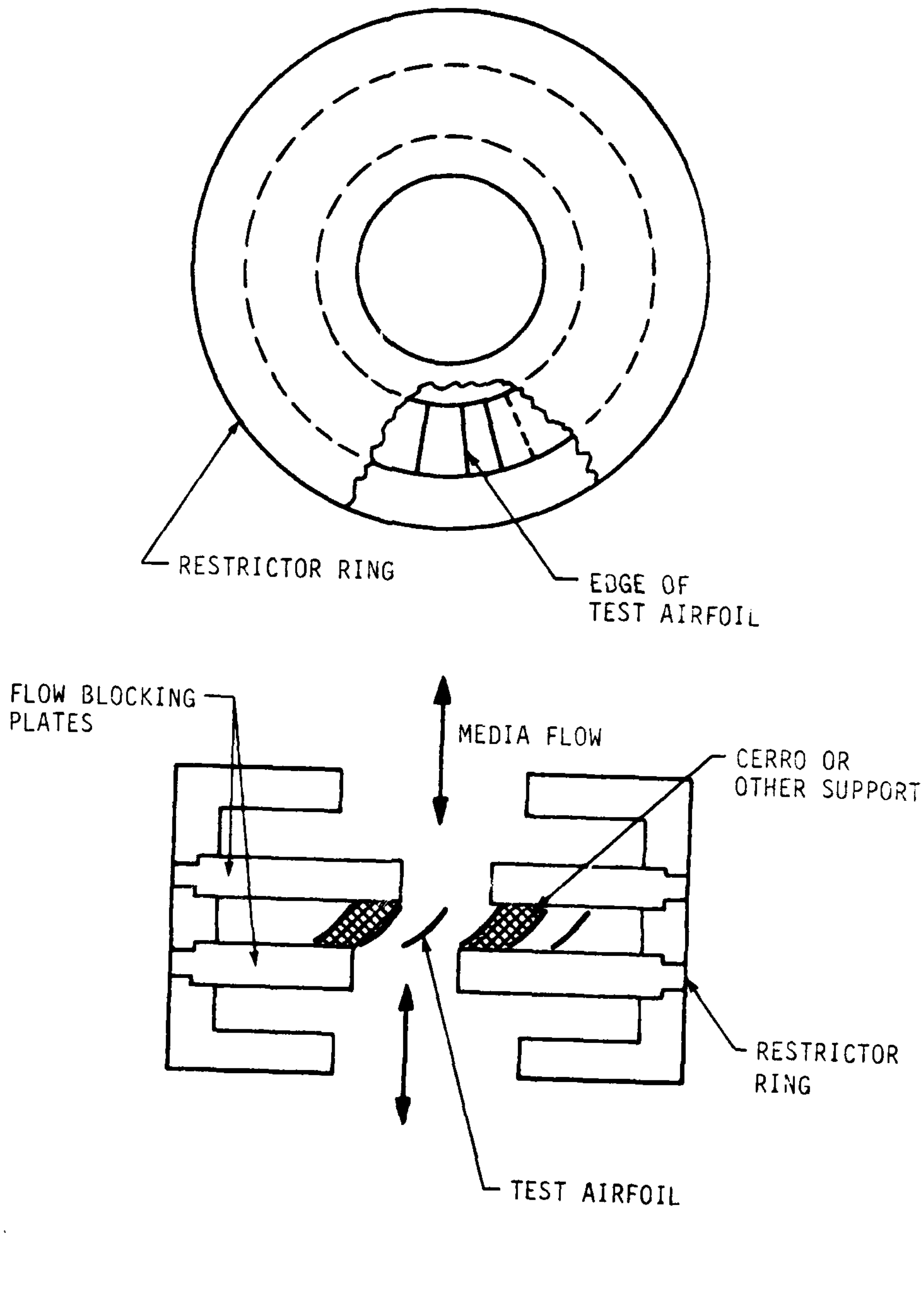



Figure 106. Stage 1 Blisk AFM Test Tool Concept.

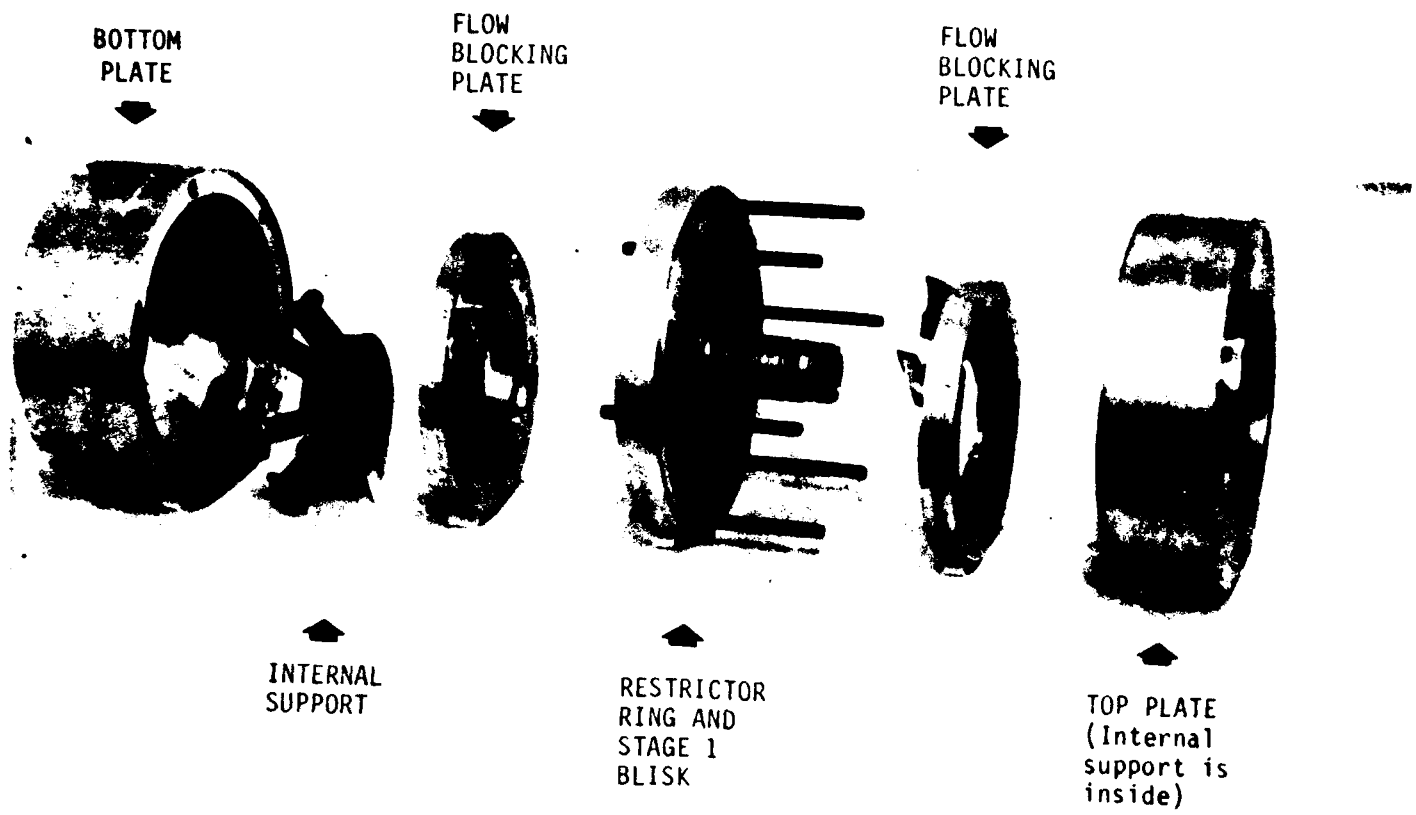



Figure 107. AFM Test Tool for Stage 1 Blisk.

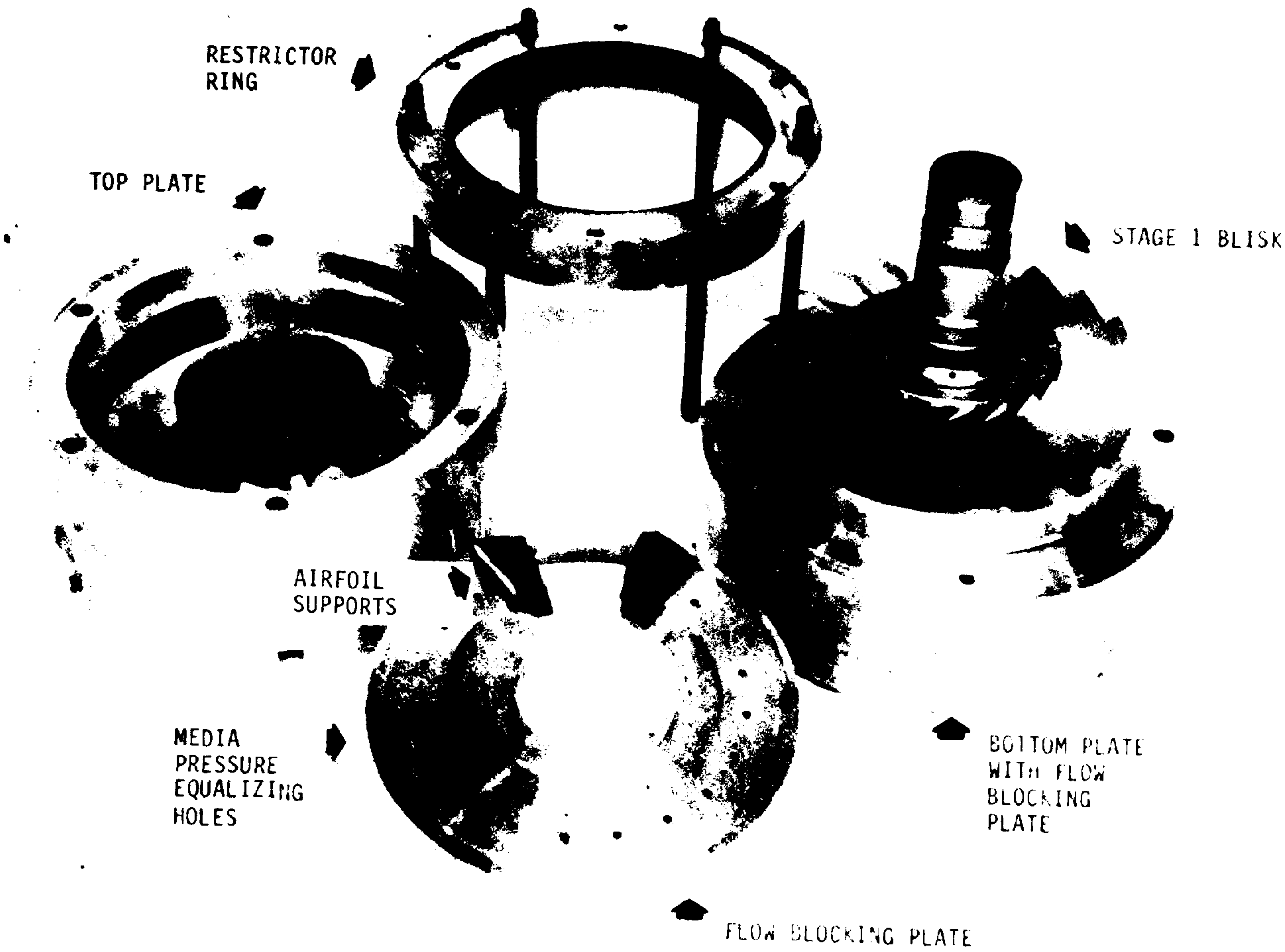

RESTRICTOR RING
TOP PLATE
STAGE 1 BLISK
AIRFOIL SUPPORTS
MEDIA PRESSURE EQUALIZING HOLES
BOTTOM PLATE WITH FLOW BLOCKING PLATE
FLOW BLOCKING PLATE

Figure [illegible]. AFM [illegible]

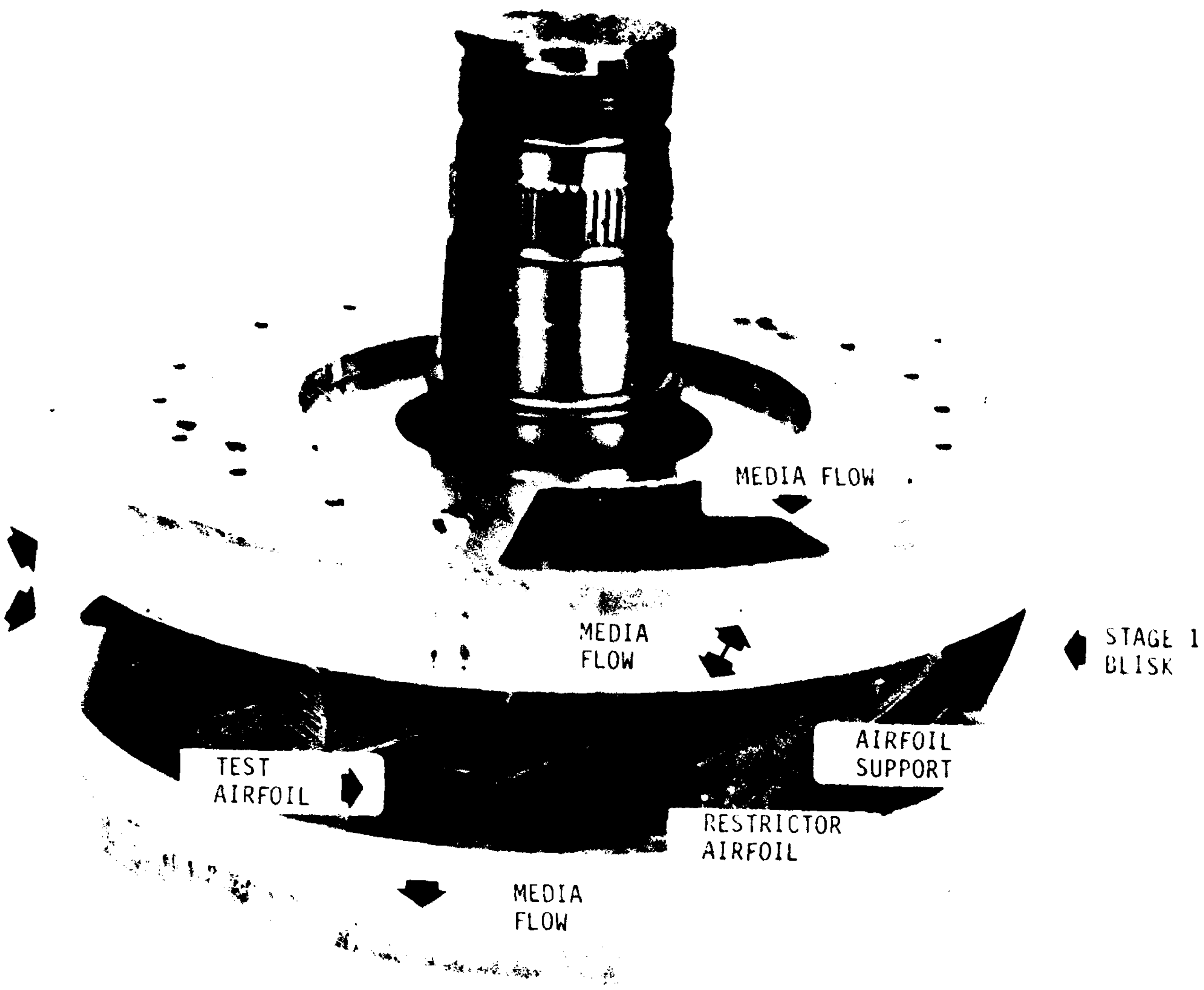
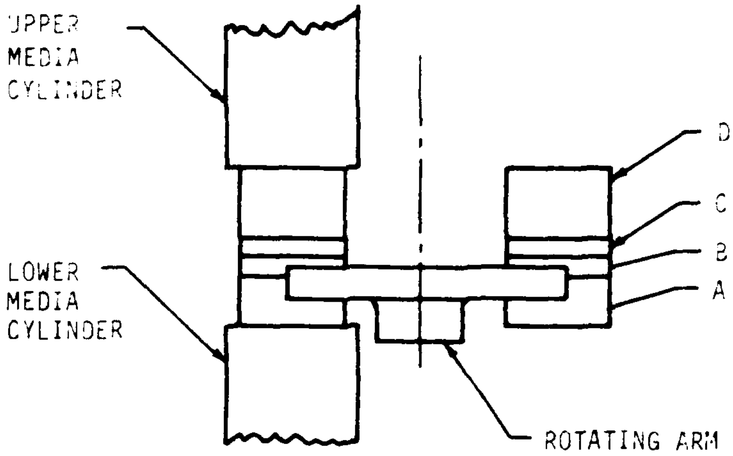
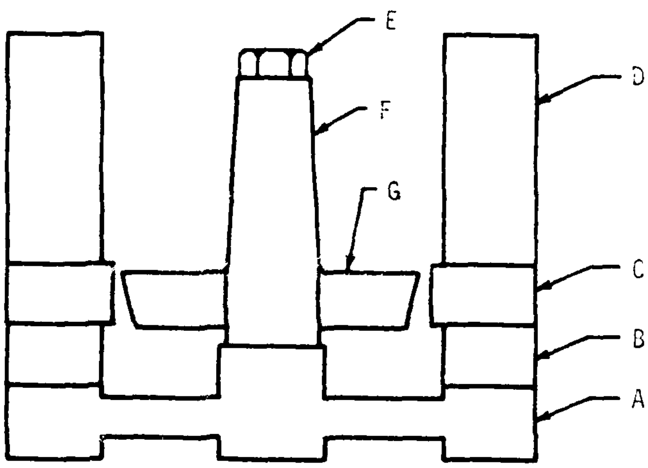



Figure 109. AFM Test Tool - Media Flow Path.




One set of tooling is in the machine while another set is being loaded or unloaded.




A - Base Ring with 6 spokes.
B - Lower Spacer.
C - Tip Restrictor Ring.
D - Upper Spacer.
E - Cap Nut (stud in Ring A is not shown).
F - Protector Cone.
G - Blisk.

Figure 110. AFM Production Tool for Stage 1 Blisk.

IMPELLER FINISHING
PROCESS DEVELOPMENT

## IMPELLER FINISHING PROCESS DEVELOPMENT

### INTRODUCTION

The process selected for impeller finishing is abrasive flow machining (AFM). This choice was based on the successfull application of this finishing process to the Stage 1 through 5 blisks.

A suitable AFM development tool was designed and produced. Extensive process development tests were then performed on scrap impellers with satisfactory results. Knowledge obtained by these tests was used to design and make a production tool. This tool was used with the production AFM machine to finish the the first impeller produced under this program, and subsequent production impellers.

### AFM DEVELOPMENT TOOL

The development tool, used in abrasive flow machining impellers, is shown schematically in Figure 112 (pg 208). The method used for adjustment of flow are is shown in Figure 113 (pg 209).

### AFM DEVELOPMENT TESTS

The depth of material removed from a surface machined by AFM is dependent on flow when media composition, pressure, and temperature are essentially constant. Flow is calculated as follows:

$$\text{Flow (in)} = \frac{\text{Media Volume Flow (in}^3\text{)}}{\text{Flow Area (in}^2\text{)}} \qquad \text{(Eq 6)}$$

Required flow was estimated from previous tests performed on INCO 718 test blocks. These data showed that depth of material removed was 1.2 mils, using the development AFM machine with 30 AFM cycles, each flowing 200 $in^3$ of media through a flow area of 0.5 $in^2$. Flow for these data is calculated as follows:

$$\text{Flow} = \frac{30 \text{ cycles X } 200 \text{ in}^3\text{/cycle}}{0.5 \text{ in}^2}$$
$$= 12{,}000 \text{ in.}$$

The estimated number of AFM cycles were calculated as follows for the production machine with a media volume of 1600 $in^3$ per cycle, and with a complete impeller in the development fixture having a flow area of 6.5 $in^2$ at the leading edges of the airfoils.

$$\text{Cycles} = \frac{\text{Flow Area (in}^2\text{) x Flow (in)}}{\text{Media Volume per Cycle (in}^3\text{)}} \qquad \text{(Eq 7)}$$

$$= \frac{6.5 \text{ in}^2 \text{x } 12{,}000 \text{ in}}{1660 \text{ in}^3\text{/cycle}}$$

$$= 47 \text{ cycles}$$

AFM DEVELOPMENT TESTS - Continued

This value was used as a guide in determining the numbers of cycles for initial test.

A number of tests were made with a scrap production impeller and the development tool, using the production AFM Machine.

The first tests were made without tool adjustment to equalize leading and trailing edge flow areas. Visual inspection of the impeller hub surfaces indicated that more material was removed from surfaces near the trailing edges, than from surfaces near the leading edges, as expected. Therefore, flow area was adjusted to make leading and trailing edge areas approximately equal for subsequent tests.

Tests conducted at 40 and 60 AFM cycles at test parameters given in Table 29 produced typical thickness and leading edge position changes shown in Figures 114-115 (pgs 210- 211).

TABLE 29
PARAMETERS FOR AFM TESTS WITH SCRAP PRODUCTION IMPELLER AND DEVELOPMENT TOOL

TEST PARAMETERS

| | | |
|---|---|---|
| Part | - | T700 Scrap Production Impeller |
| Machine | - | HL60CF-830 |
| Tooling | - | Development Tool |
| Media | - | D080-20A(61), - 36A(73), - 700(40) Reworked |
| Media Temperature | - | 79°F Average |
| Media Pressure | - | 200 psi |
| Total Cycles (Test No. 1) | - | 40 |
| Total Cycles (Test No. 2) | - | 20 |
| Total Time (Test No. 1) | - | 72 Minutes |
| Total Time (Test No. 2) | - | 37 Minutes |

Note

This impeller was abrasive flowed in two operations. First operation was for 40 cycles, and after thickness and leading edge position checks were made, a second operation of 20 cycles was applied.

Thickness reductions averages 1.5 mils for the second test at 20 AFM cycles, and only 0.7 mils for the first test at 40 cycles; it is possible that the original surface of the airfoils was harder as the result of strain hardening by machining, which is characteristic of INCO 718 material.

Different leading edge contours were produced on scrap impellers by filing. These were photographed before and after AFM tests. Examination of leading edge contours showed that edges which were not symmetrical before AFM were not made symmetrical by AFM, although they showed smoother contours. These results indicated that symmetrical edges should be produced by contour milling. Leading edge contours, produced by AFM from various contours before AFM are shown in Figures 116-117 (pgs 212-213). Changes in airfoil tip edge radii, produced by AFM are shown in Figure 118 (pg 214).

AFM DEVELOPMENT TESTS - Continued

Following these tests, impeller airfoils and hub surfaces, milled with the 5-axis, 4-spindle development machine, were abrasive flow machined using the AFM development tool. The average depth of material removed was approximately 0.5 mil, based on measurements of airfoil thickness changes, and average thickness reduction was two times this value or about 1 mil.

AFM of First Impeller Produced For Engine Testing

Extensive measurements were made of finished geometry and surface roughness, after benching and AFM with the production machine, of the first impeller for engine testing. They indicated that acceptable impeller characteristics are obtainable for the surface finishing process. The AFM machining parameters are given in Table 30.

TABLE 30
AFM MACHINING PARAMETERS

| | | |
|---|---|---|
| Machine | - | Dynetics Production - NL60CF-830 |
| Tooling | - | Production Tooling |
| Media | - | D080-20A(61), - 36A(73), - 700(40) |
| Media Temperature | - | 80°F Average |
| Media Pressure | - | 150 psi |
| Total Cycles | - | 52 |
| Total Time | - | 95 Minutes |

Some difficulty was encountered in obtaining satisfactory leading edge contours after AFM, due to excessive airfoil thickness prior to this process, and due to the nonconformance of contours, prior to AFM, to the requirements shown in Figure 119 (pg 215). It was found that, when edges are prepared properly for AFM, contour design limits could be met when airfoil thickness is reduced, as indicated in Figure 119.

Final surface roughness of airfoils was typically reduced by AFM from a milled roughness of approximately 40 to 60 microinches, to a roughness after AFM of less than the required 32 microinches. Typical roughness measurements, after AFM, are given in Figure 120 (pg 216) for airfoils and hub surfaces. Benching of hub surfaces was done to reduce roughness, with a hand held tool which drives a small grinding wheel.

Results with the first impeller indicated that conformance improvements were needed in airfoil thickness, airfoil leading edge position, and contour, and hub contour and waviness. These improvements were obtained by changes in NC programming and milling, and were demonstrated on production impellers subsequently produced with the first production milling machine. No improvements in the AFM finishing process were made.

PRODUCTION AFM MACHINE REQUIREMENTS

Production AFM machine requirements were established as a part of this program. They are identical to those for blisks, and are given in the specification included as Appendix B (pgs 343-354).

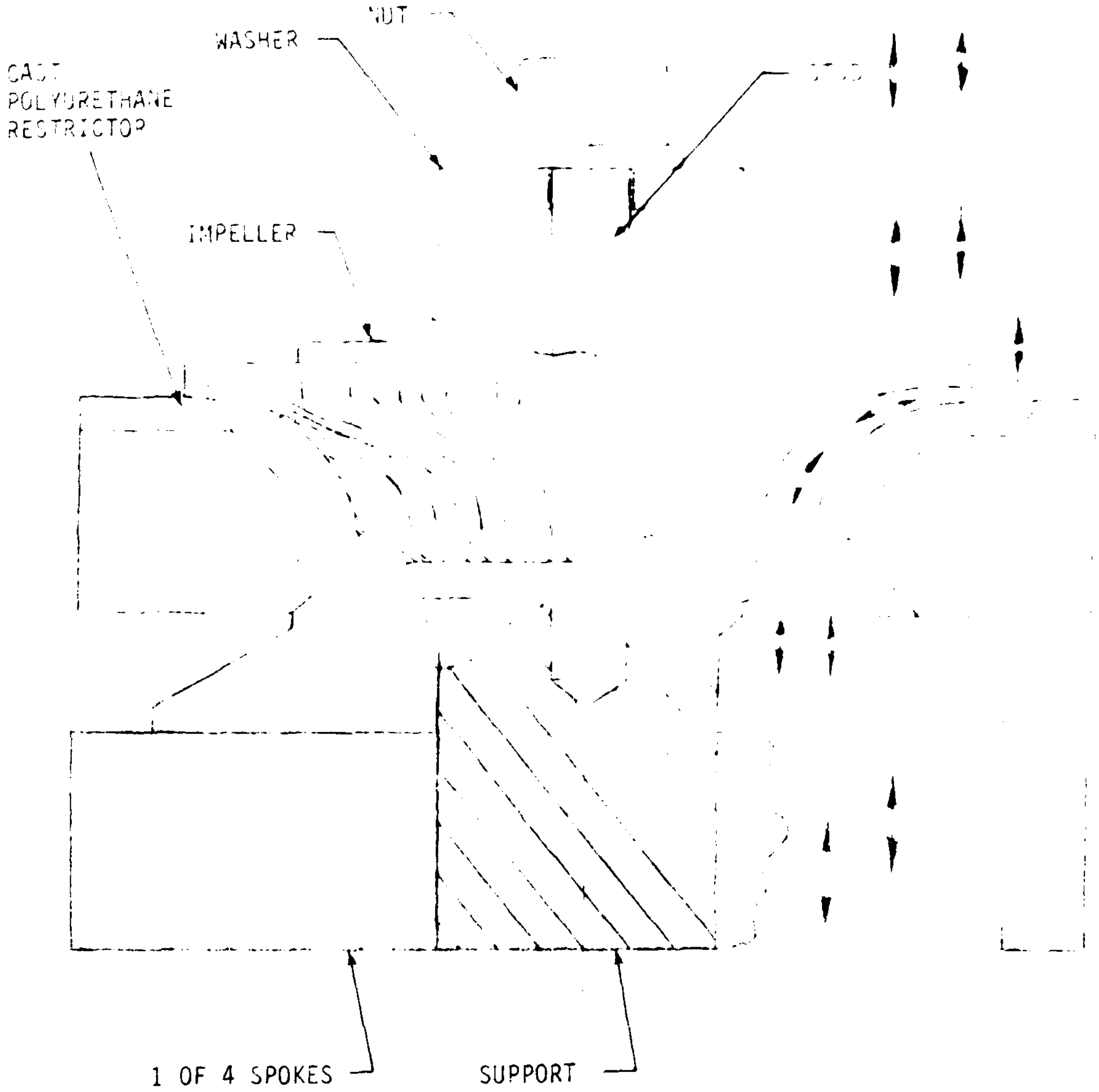
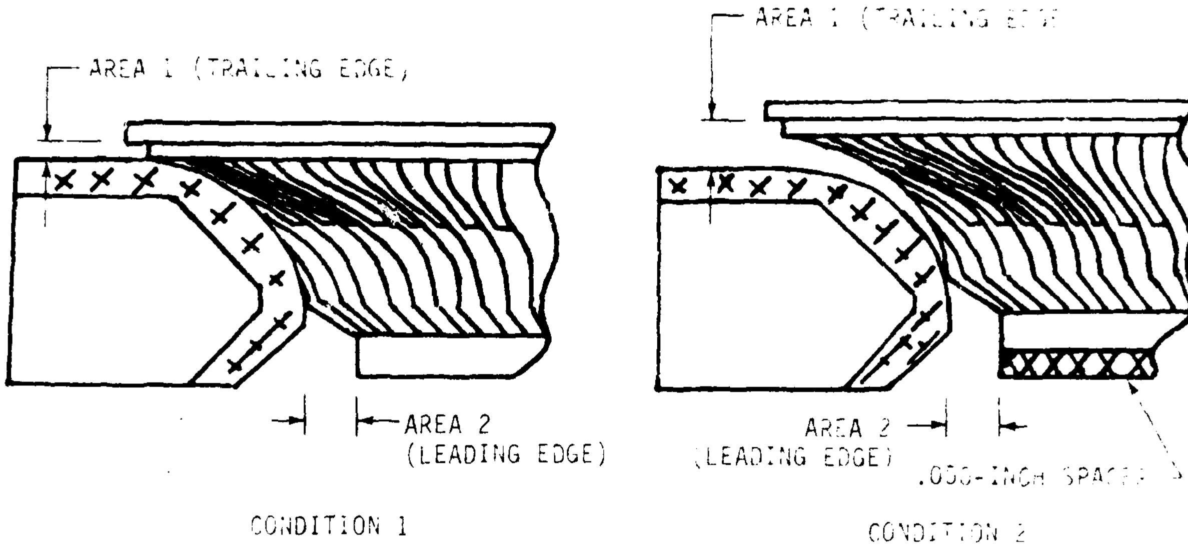


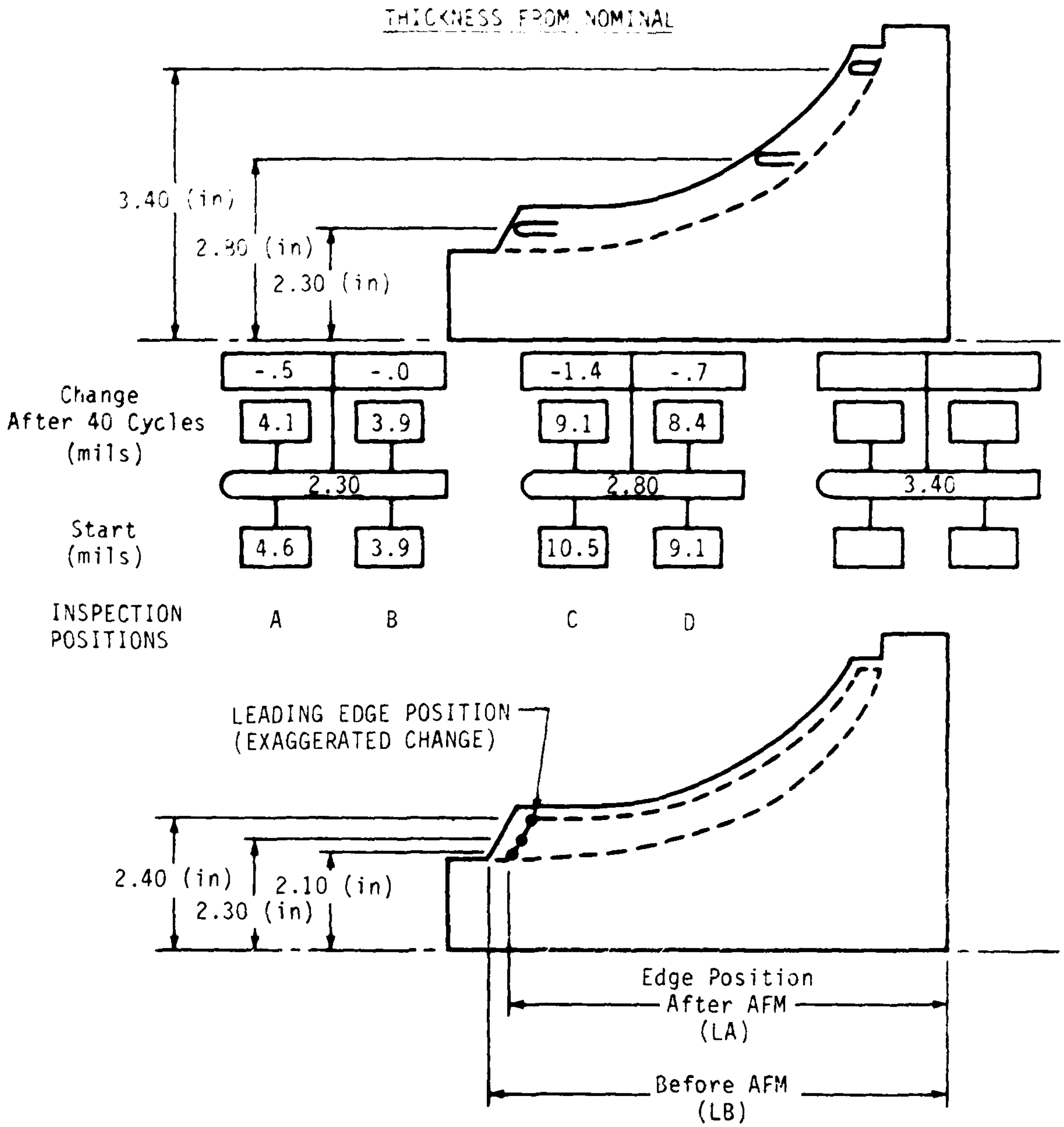

Figure 112. Impeller AFM Development Tool.




Condition 1 - Without flow area adjusted,
Area 1 < Area 2.

Condition 2 - With flow area adjusted,
Area 1 ≈ Area 2.

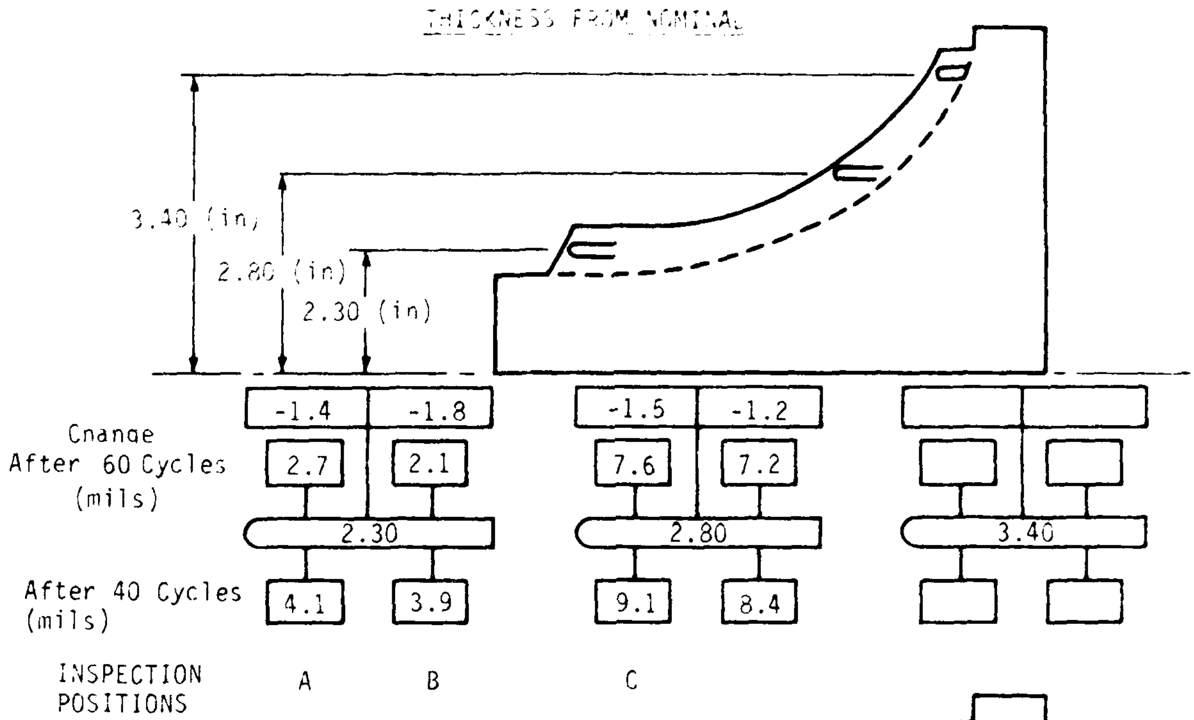
Figure 113. Adjustment of Flow Area in Impeller AFM Development Tool.

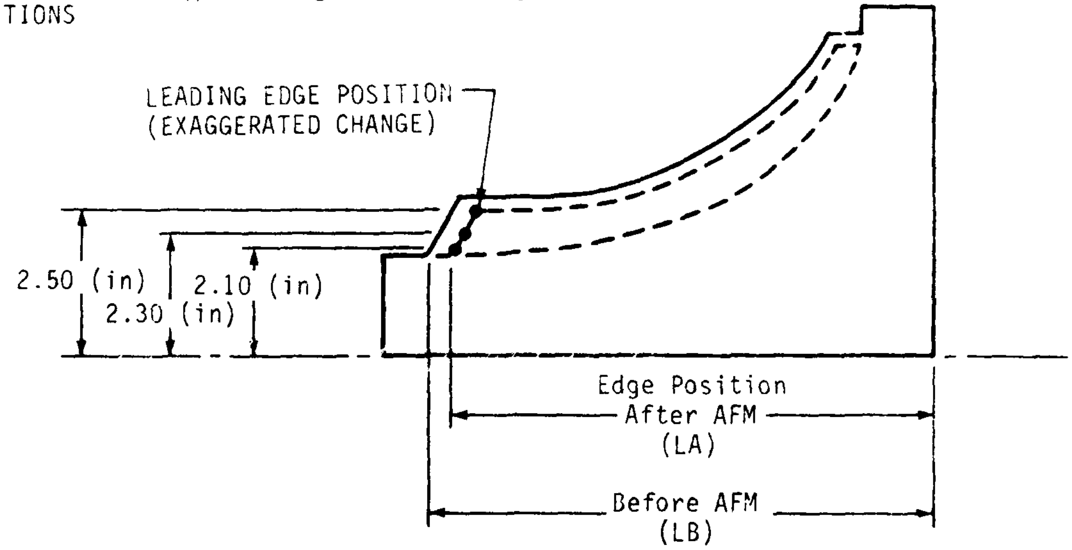



TEST NO. 1
FULL AIRFOIL 3

| | LA (mils) | LB (mils) | ΔL (mils) |
|---|---|---|---|
| 2.10 (in) | 5.227 | 5.227 | -.000 |
| 2.30 (in) | 5.147 | 5.149 | +.002 |
| 2.50 (in) | 5.076 | 5.076 | -.000 |

Figure 114. Typical Changes in Impeller Airfoil Thickness and Leading Edge Position by Abrasive Flow Machining.

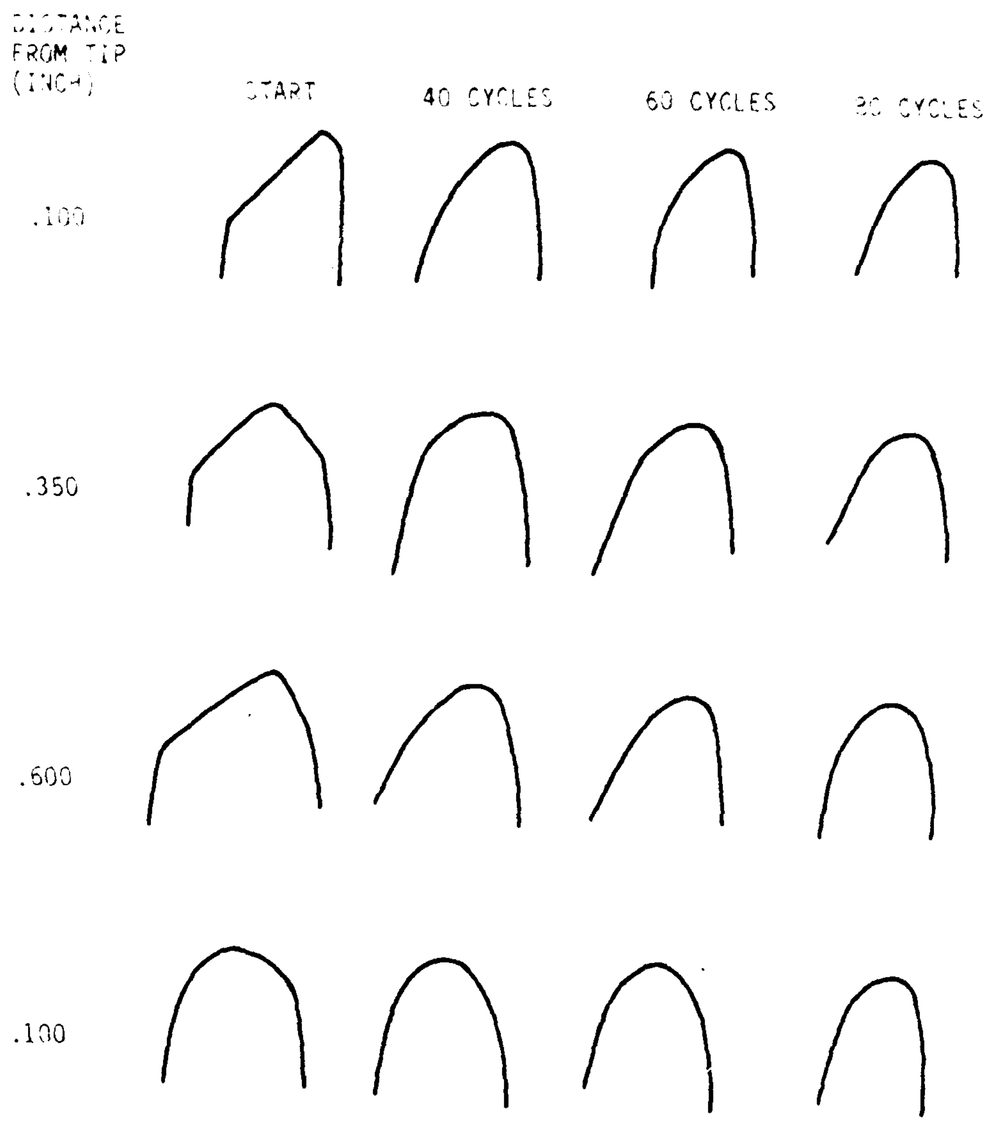



TEST NO. 2
FULL AIRFOIL 3

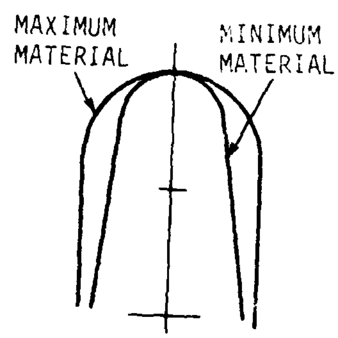
| | LA (mils) | LB (mils) | ΔL (mils) |
|---|---|---|---|
| 2.10 (in) | 5.227 | 5.222 | -.005 |
| 2.30 (in) | 5.147 | 5.142 | -.005 |
| 2.50 (in) | 5.076 | 5.071 | -.005 |

Figure 115. Typical Changes in Impeller Airfoil Thickness and Leading Edge Position by Abrasive Flow Machining.



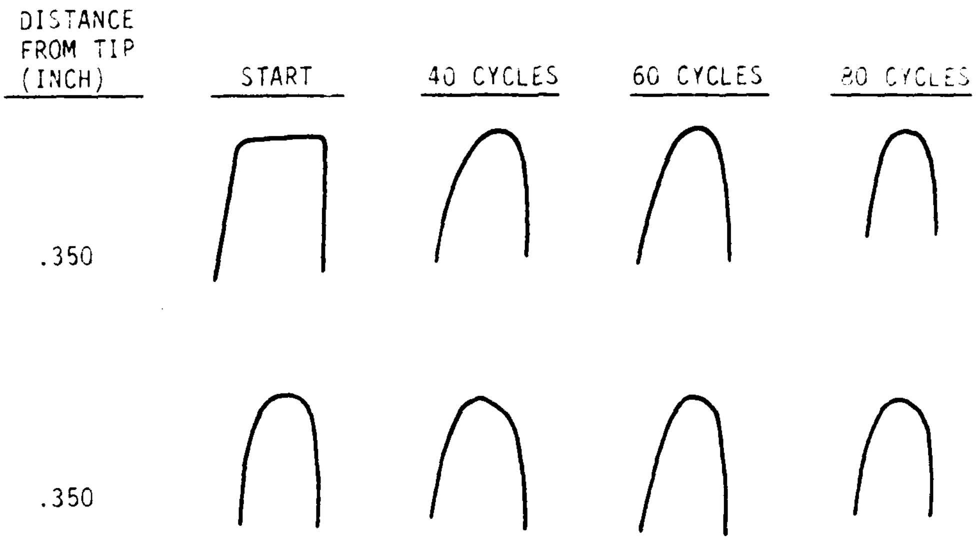

AFM PARAMETERS
Part - T700 Scrap Impeller
Machine - HL60CF830
Tooling - Impeller Development Tool
Media - D080-20A(61)-36A(73)-700(40)
Media Temperature - 79°F average
Media Pressure - 200 psi
Time - 40 cycles - 72 minutes
Time - 60 cycles - 109 minutes
Time - 80 cycles - 129 minutes

Note:- Edge geometries presented above are tracings of light section photographs.




TYPICAL IMPELLER AIRFOIL LEADING EDGE GEOMETRY REQUIREMENTS

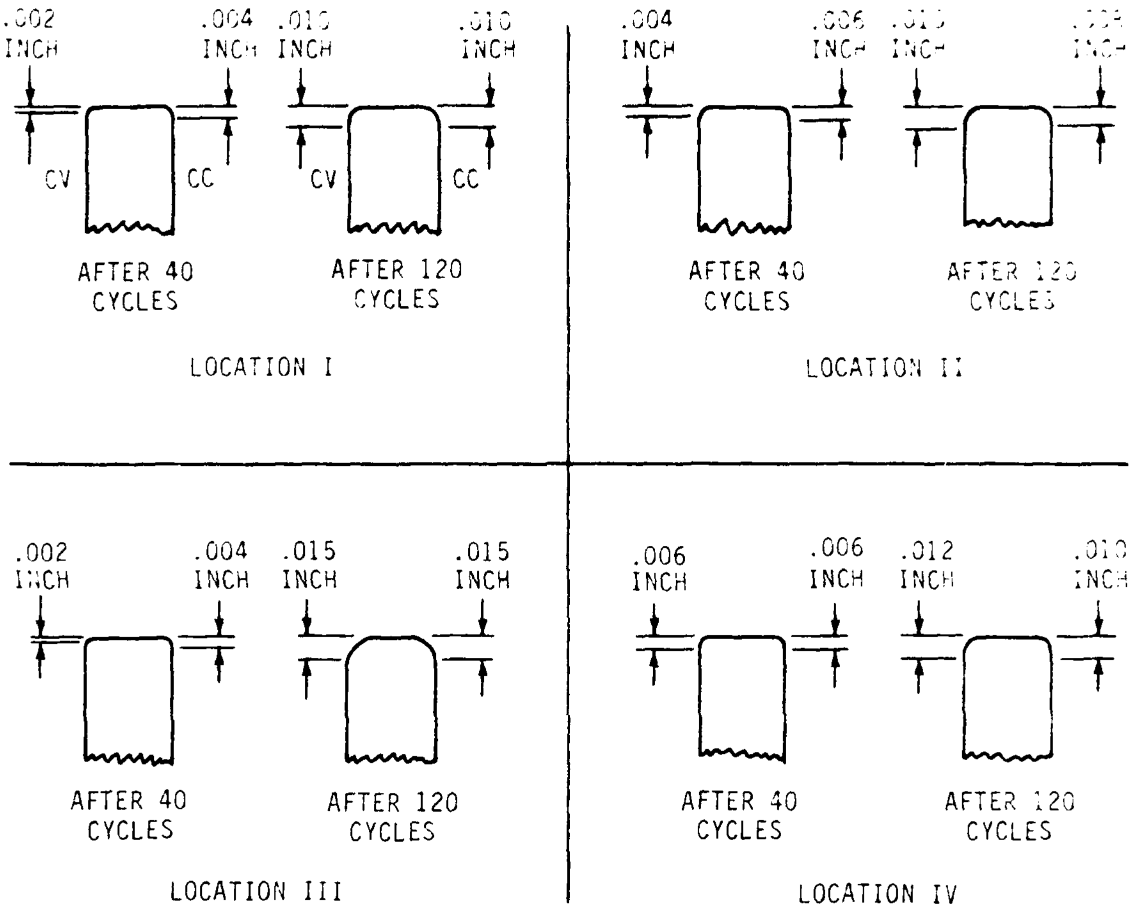
Figure 116. Effect of AFM on Impeller Full Airfoil Edge Geometry.



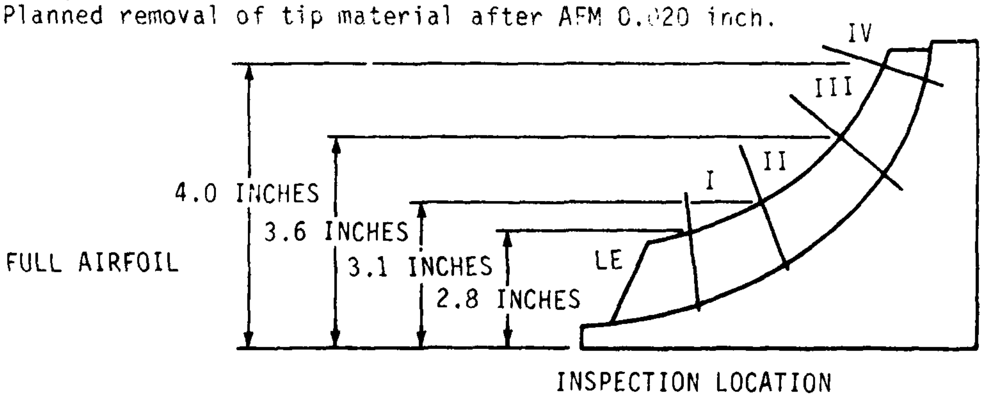

AFM PARAMETERS
Part - T700 Scrap Impeller
Machine - HL60CF830
Tooling - Impeller Development Tool
Media - D080-20A(61)-36A(73)-700(40)
Media Temperature - 79° average
Media Pressure - 200 psi
Time - 40 cycles - 72 minutes
Time - 60 cycles - 109 minutes
Time - 80 cycles - 129 minutes

Note: Edge geometries presented above are tracings of light section photographs.

Figure 117. Effect of AFM on Impeller Splitter Airfoil Leading Edge Geometry.

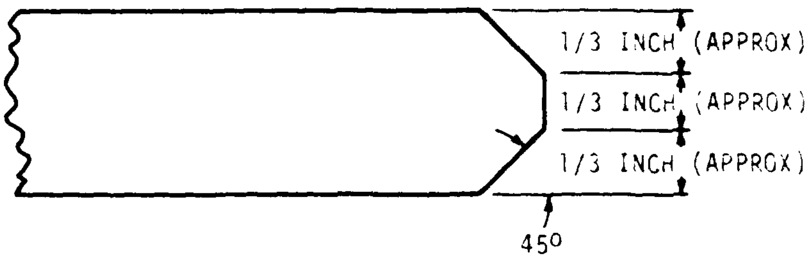



Design limit 0.005 inch.
Planned removal of tip material after AFM 0.020 inch.

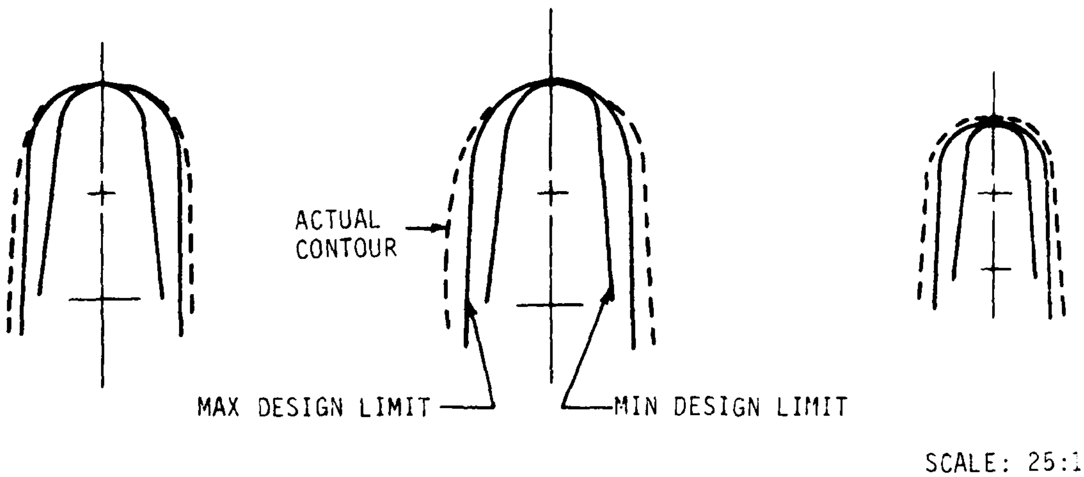



AFM parameters same as Figure 116

Figure 118. Airfoil Tip Radii Produced by AFM on Scrap Productions Impeller.




APPROXIMATE LEADING EDGE CONTOUR REQUIRED BEFORE AFM




Tracings of photographs of typical leading edge contours after AFM when edges were benched to required contour before AFM

Figure 119. Attainable Leading Edge Contours After Benching and AFM of Airfoils.

T700 IMPELLER DEVELOPMENT INSPECTION

AIRFOIL SURFACE ROUGHNESS

SER. NO. GLB 83193   INSP. BY W.W.G.   DATE 10-3-78

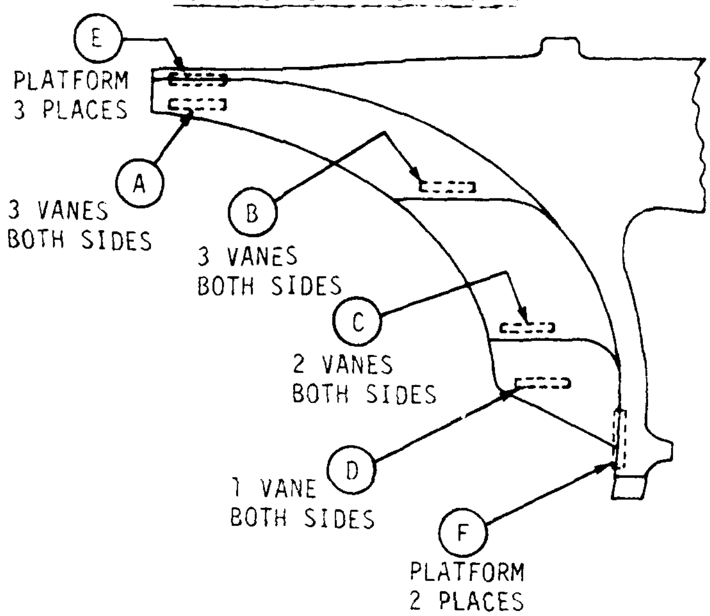
SET-UP AND INSPECT PER WI MG 6 1978 USING BENDIX PROFILOMETER

**DRAWING REQUIREMENTS**

$\sqrt[32]{}$ on airfoils and platform (Ref Sect JJ, Zone A-13)

Drg. Note 10: "Surface Finish Requirements Apply Before Peening"

**LOCATION OF MEASUREMENTS**




| | AIRFOILS A | AIRFOILS B | AIRFOILS C | AIRFOILS D | HUB E | HUB F |
|---|---|---|---|---|---|---|
| **PRESSURE SIDE*** | | | | | | |
| 0° FULL VANE | 15 | 18 | 10 | 63 | 22 | 40 |
| -8° SPLITTER | 17 | 22 | 20 | – | 17 | – |
| -16° HALF SPLITTER | 19 | 22 | — | — | 26 | — |
| **SUCTION SIDE** | | | | | | |
| 0° FULL VANE | 13 | 27 | 14 | 17 | – | 40 |
| -8° SPLITTER | 18 | 23 | 24 | – | – | – |
| -16° HALF SPLITTER | 25 | 22 | - | - | - | — |

**COMMENTS**

Hub surface roughness being reduced by additional benching.

*"Pressure Side" is the left - hand side of an airfoil looking aft.

Figure 120. Surface Roughness After Benching and AFM of Airfoil and Hub Surfaces.

INSPECTION PROCESS
DEVELOPMENT

# INSPECTION PROCESS DEVELOPMENT

## INTRODUCTION

The purpose of this task was to provide effective gaging equipment to make possible the development of blisk and impeller machining. The complex shapes and close tolerances of blisks and impellers present significant challenges to effective inspection process.

Several alternatives were explored, to ensure optimum results. These were ultimately distilled down to two basic techniques:

1. Dual-probe mechanical tracing and airfoil contour replication on coated glass, which is projected on a conventional optical comparator.

2. Light sectioning, using a 40 magnification microscope, for inspection of airfoil leading and trailing edge profiles.

## SYSTEMS FOR TRACING AIRFOIL CONTOURS

### Investigation of Alternatives

A procurement specification (General Electric AQCE Specification No. 11-75-2) was generated and submitted to several vendors for quotes on systems capable of performing accurate tracing of airfoils. Several proposed techniques were evaluated. The following were typical of the responses received to the solicitation:

1. A system was offered by Centerline Precision Manufacturiang Co., utilizing mechanical tracing and contour replication on coated glass, which is projected on a conventional optical comparator. This system provides a hard copy of the mangnified airfoil tracings.

2. An airfoil inspection system, offered by Jones and Lamson Corporation consisting of a numerically controlled table, a process computer for data handling, a special tracer and a 30-inch optical comparator.

3. An airfoil contour tracer, manufactured by New England Airfoil Machining Operations. This machine had potential as an inspection device for blisk airfoils. However, the system had no potential for impeller measurements.

4. A system proposed by Automation Gages, Inc. and Optical Gaging Products, utilizing a ball slide tracer in an optical comparator for blisk and impeller airfoils and airflowpath parameters. A second system utilizing mechanical tracking and replication of airfoil shape on frosted glass was also quoted.

The result of evaluations conducted on these proposals indicated that the Centerline Precision Manufacturing Company tracer machine was the most appropriate for the needs of this Program. Accordingly, an order was placed with this company to furnish this equipment. The completed equipment is shown in Figure 121 (pg 221).

SYSTEMS FOR TRACING AIRFOIL CONTOURS - Continued

The Centerline Tracer is capable of tracing all blisk and impeller airfoils as well as axial flow path contours. Prior to commencing measurements, the blisk or impeller is fixtured to a compound rotary table. Predetermined radial section heights and warp angles are set and a dual mechanical tracer is power-driven across the airfoil. an exact 1-tool reproduction of the airfoil shape is duplicated on specially coated glass. The glass is then transferred to an optical comparator and the shape is projected at 10 or 20 magnifications and compared to a 10X or 20X magnification master chart. A typical tracking is shown in Figure 122 (pg 222).

This technique provides a semi-permanent record of the airfoil shape. Determinations of warp angle, thickness, contour, and true position can be assessed with minimum operator influence on data acquisition.

The Centerline Tracer requires various accessories for the inspection of blisks and impellers. These include special holding fixtures, comparator charts, and coated glass masters.

Early tests conducted with the airfoil tracing machine, showed that the scribed line quality was excellent and the related coated glass process provided outstandingly crisp and well-defined lines. Following some use, however, it was necessary to modify the machine extensively to improve accuracy and operating effectiveness. The principal improvement made in connection with operating effectivenes was the addition of a digital readout device for the radial position of the tracing probes. Other modifications, made to overcome problems with repeatability and accuracy, included the following:

1. Relocate and strengthen upper structure.

2. Replace retracting cylinders.

3. Provide for positive anti-rotation on cylinders.

4. Make new steel scriber holders

5. Rework scribe box.

6. Correct linearity on scriber knobs.

Centerline Tracer Machine Tests

The modified airfoil tracking machine was checked out for alignment and function. A major problem in glass coating quality was identified and corrected.

Repeatability and accuracy tests were performed on the tracing machine by two operators. Thirteen traces were generated and 208 observations were made with them to evaluate contour, thickness, and pattern repeatability. The tests were performed on a straight-sided master which was not removed from the system between runs. Analysis of results gave information on system thickness and contour measurement accuracy capability.

SYSTEMS FOR TRACING AIRFOIL CONTOURS - Continued

The first airfoil machined on the five-axis NC development machine was traced, and the tracing was compared with a master. Deviations from the master were then compared with results of the capability test. Using knowledge obtained from this work, it was determined that probe design could be improved to obtain best accuracy when tracing airfoils. A new probe design was established and fabricatied.

Capability of the system with the new design probes was evaluated by again tracing the straight-sided test master. the test results showed that the system had a thickness measurement accuracy of $\pm 0.3$ mils and a contour measurement accuracy of $\pm 0.5$ mils.

EQUIPMENT FOR LEADING AND TRAILING EDGE INSPECTION

At the outset of the Development Program, the only known measuring technique that could provide good leading and trailing edge definition was light sectioning through the use of optics. This method has been applied successfully in production inspection of conventional blade and vanes.

Plans were made to explore the possibility of modifying existing light sectioning equipment for this Program. Accordingly, a specification was generated and proposals were solicited for the necessary work. The selected vendor modified the existing equipment and refitted it with new optics to increase the magnification to 40X.

Figure 123 (pg 223) shows a view of the light sectioning microscope for inspection of leading and trailing edge profiles. Figure 124 (pg 224) shows a close-up view of a light sectioned blisk blade. A typical profile of an airfoil leading edge contour after abrasive flow machining is shown in Figure 125 (pg 225). A typical reticle used for contour inspection is shown in Figure 126 (pg 226).

OTHER INSPECTION SYSTEM INVESTIGATIONS

Computer Controlled Coordinate Measuring System

During the initial search for an airfoil contour inspection system, it was realized that a computer-controlled coordinate measuring system would be desirable for accurate inspection of airfoil contours. The inherent advantages of this type of system over know mechanical, electronic and optical techniques, in terms of repeatability, generation of data and elimination of operators bias, indicated a high potential for this application. Accordingly, the Bendix Corporation was approached with regard to the application of its Direct Computer Controlled Cordax (DCCC) inspection machine for this task.

OTHER INSPECTION SYSTEM INVESTIGATIONS - Continued

To facilitate an understanding of the requirements, Bendix was supplied with sample parts and a computerized definition of a typical airfoil. In addition, direct discussions covered problems in tooling, probing, programming, data acquisition and handling, and manufacturing methods versus drawings definitions.

A Bendix DCC 3000 machine was acquired and the contours of a master blade were stored in its memory. Measurements were performed on two other blades and comparisons were made between them and the master blade.

Preliminary results indicated that this technique could provide useful data for evaluations of airfoils. However, the cost and time for implementing the system, compared with the Centerline Tracer system, was expected to be too great. Accordingly, development of the computer-controlled coordinate measuring system was discontinued.

### On-Machine Inspection

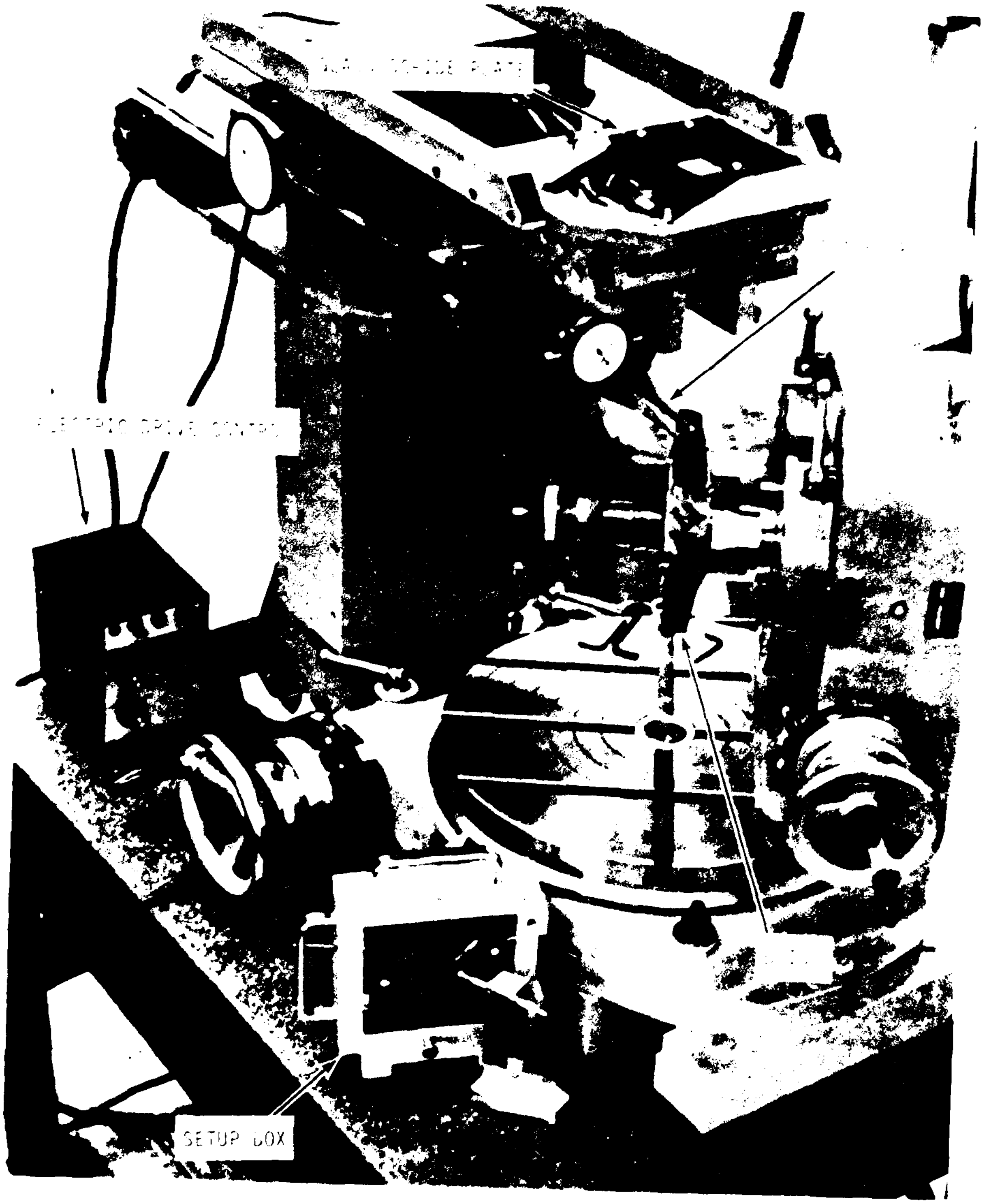
The possibility of using the 5-axis, 4-spindle development milling machine as an inspection device was investigated with New England Machine Co. That firm had developed an electro-mechanical tracer with a 3-axis stylus and applied it to its tracer mills.

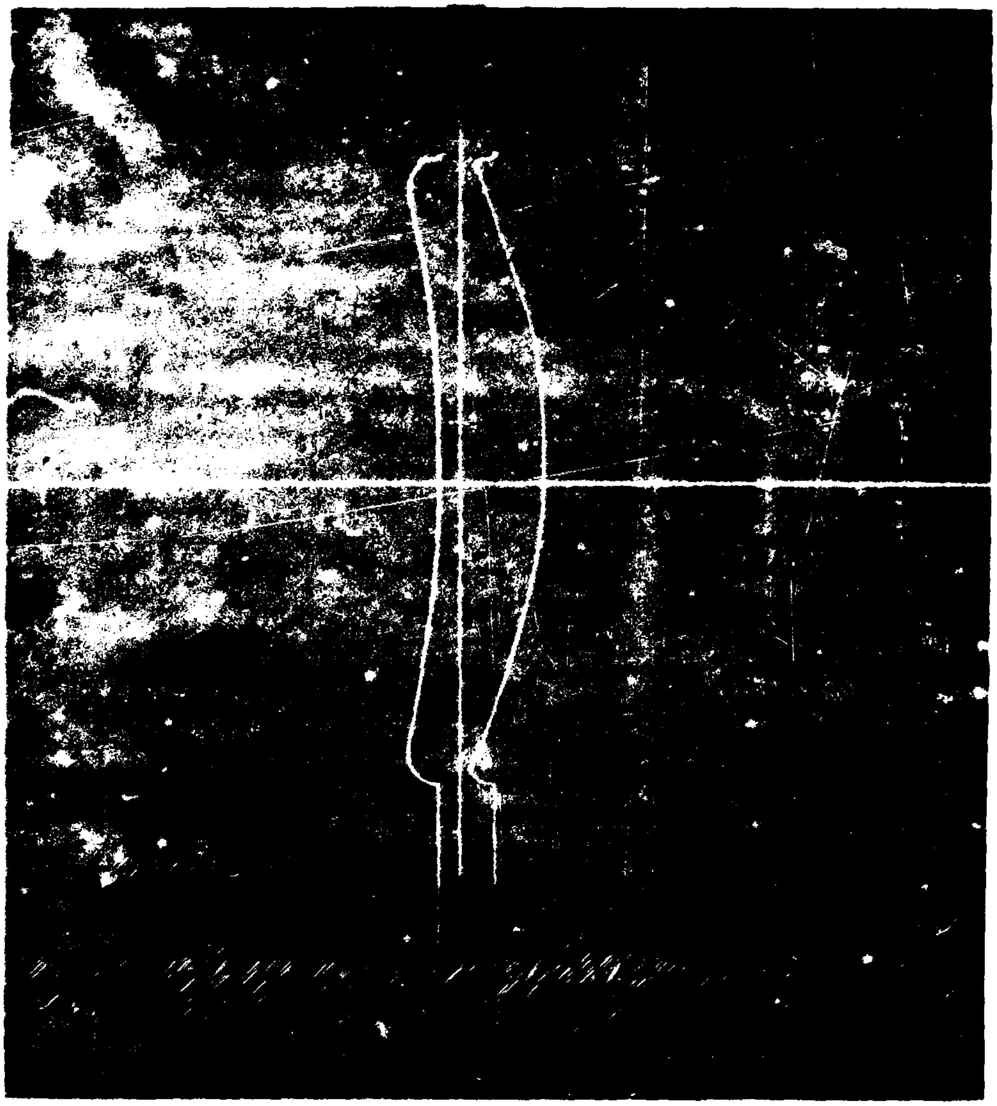
Layouts, probe and tooling designs and application concept were discussed and a minimum risk approach was formulated. A tracer probe was bench tested and the results were encouraging. Preliminary tests indicated that a probe exerting a gaging force of one ounce on the airfoil could be produced. Airfoil contour data would be presented on an oscilloscope.

Following further development and testing of the on-machine probe, it was concluded that plans to implement this technique should be discontinued. This decision was due, in the main, to the availability of the Centerline Tracer system.

## PRODUCTION INSPECTION EQUIPMENT REQUIREMENTS

Production inspection equipment requirements were established as part of this program. They are given in the specifications included at Appendix C (pgs 355-377). A five axis computer numerically controlled process was selected for measurement of all dimensional characteristics (excepting leading edge contour), because it can be readily adapted to any airfoil design within a wide range of sizes, and can be highly automated for maximum productivity.


SETUP BOX



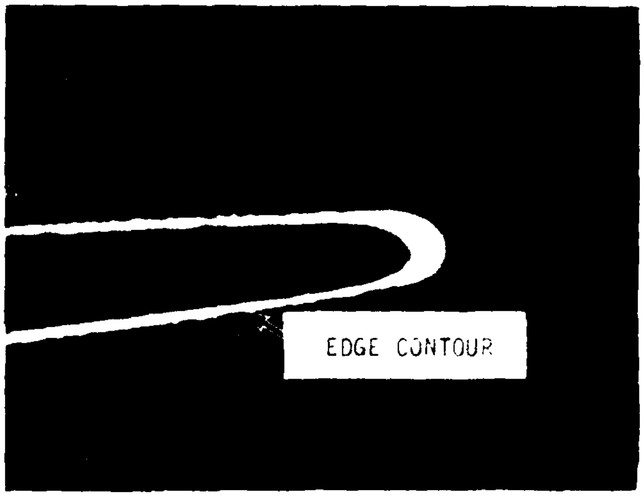
1) The airfoil stacking axis is at the intersection of XX-YY.

2) The above is a tracing of a Stage 1 blisk airfoil at Section BB as made by a tracer probe with a 0.1250 inch tracer disk. The traced airfoil thickness is greater than airfoil thickness by the diameter of the disks. Scale: Approx 2X magnification.

Figure 1[illegible]. Typical Blisk Airfoil Tracing.


Figure 123. Light Sectioning Microscope for Leading Edge Profile.

Figure 124. [illegible] blade.




Scale: 20X magnification.

Note:
Edge contour is inside the lighted area.

Figure 125. Light Section of an Airfoil Edge.

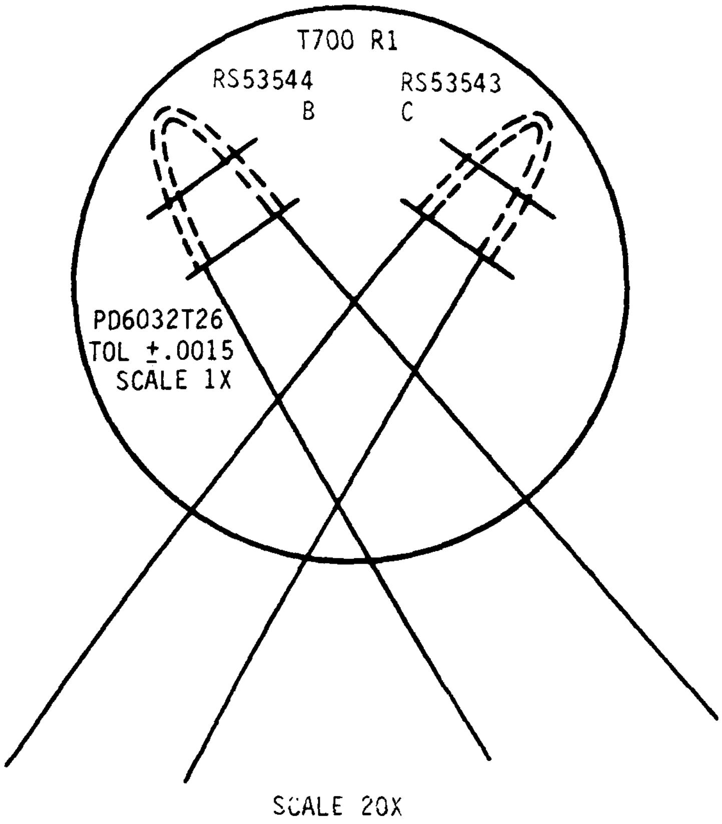



Figure 126. Microscope Reticle for Sections B and C
Stage 1 Blisk Leading Edge.

PROCESS CAPABILITY

STAGE 1 BLISK

# PROCESS CAPABILITY

## INTRODUCTION

Extensive investigations were conducted to determine process capability for the combination of NC milling, and abrasive flow machining for Stage 1 through 5 blisks and the impeller. Statistical analyses were performed on selected measurements taken on finished blisks and impellers. The results of this work show that satisfactory process capability was achieved for these parts.

## STAGE 1 BLISK PROCESS CAPABILITY

All airfoils platforms were milled on the first complete Stage 1 blisk, produced during the course of this development program, using the 5-axis, 4-spindle NC development milling machine. They were then finished with the production AFM machine and fixture. This blisk was made for engine testing.

The airfoils and platforms were produced by milling pockets in three steps as shown in Figure 127 (pg 233); parametes used are given in Table 31 (pg 228). Abrasive flow machining parameters are given in Table 32 (pg 229). Measurements of airfoil geometry, after milling and after abrasive flow machining, are summarized in Tables 33-34 (pgs 230-231). Platform flow path contour measurements are shown in Tables 35-36 (pg 232). Typical airfoil surface roughness data are given in Figures 128-129 (pgs 234-235). Typical airfoil and platform fillet radius measurements are given in Figures 130-131 (pgs 236-239). Typical airfoil geometry measurements are given in Figure 132 (pg 240). All leading edge contours were within design limits.

No problems were encountered with the operation of the NC program in producing the 20 airfoils and platforms on this part, nor with airfoil or platform finishing cutters. One roughing cutter broke while cutting; this was attributed to improper grinding of the end cutting edges. Cutter usage is shown in Figure 127 (pg 233). Abrasive flow machining was performed without difficulty.

Measurements indicated that geometry was generally within design limits, and that milled airfoil surface roughness was within the capability of abrasive flow machining to produce finished surface roughness within design limits. Principal deviations from limits were: thickness limits were exceeded by 1 to 7 mils at the airfoil section closest to the platform, and 1 to 3 mils at a small percentage of measured locations at other sections. Thickness of the section closest to the platform was programmed to be 8 mils greater than thickness of the other sections of the airfoils to assure that this section which is milled with the platform cutter, would not be thinner than other sections which are milled with the airfoil finish cutter.

TABLE 31
CUTTING PARAMETERS USED FOR MILLING AIRFOILS AND PLATFORMS ON STAGE 1 BLISK FOR ENGINE TESTING

| Operation | Cutting Speed (sft/min) | Lineal Feed (inch/min) | Downfeed (inch/pass) | Depth of Cut (inch) | Cutter Extension (inch) | Cutter Geometry No. Flutes | Helix Angle (deg) | Rake Angle (deg) | Relief Angle (deg) |
|---|---|---|---|---|---|---|---|---|---|
| Airfoil Rough Contour Milling | 184 | 2.4 | .120 | .312 Step Cut | 2.0 | 6 | 30 | 0 | 6 |
| Airfoil Finish Contour Milling | 147 | 15 | .010 | .020 | 2.0 | 12 | 30 | 30 neg | 45 |
| Platform Finish Contour Milling | 196 | 15 | .010 | .010 | 2.2 | 12 | 30 | 30 neg | 45 |

NOTES:

Blank Material - AM355
Blank Hardness - 34-36Rc
Cutter Material - Carbide Grade 883

STAGE 1 BLISK PROCESS - Continued

TABLE 32

AFM PARAMETERS USED TO FINISH AIRFOILS AND PLATFORMS OF STAGE 1 BLISK FOR ENGINE TESTING

AFM PARAMETERS

| | | |
|---|---|---|
| Machine | - | Dynetics Production - HL60CF-830 |
| Tooling | - | Production Tooling |
| Media | - | Dynetics - DOMO-20A (61), 36A(73) - 700(40) |
| Media Temperature | - | Start 95°F, End 104°F (First 50 cycles)<br>Start 98°F, End 116°F (Final 25 cycles) |
| Total Cycles | - | 75 |
| Media Pressure | - | 150 psi |

BLISK

Stage 1 Serial Number WYM 78114

Statistical Analysis of Airfoil Thickness

A statistical analysis, based on normal distribution, was made of airfoil thickness measurements obtained from the first Stage 1 blisk produced for engine testing, to obtain an evaluation of process capability. Results showed that essentially 95% of thicknesses of all airfoils on this blisk measured at three defined sections not including the section closest to the platform, should fall within design limits.

Thickness analysis results are shown in Figure 133 (pg 241). The reduction in milled airfoil thickness by abrasive flow machining, is shown by the reduction of the mean thickness from +1.95 mils to +1.00 mil with respect to design nominal. The finished airfoil mean of +1.00 mil is very close to the design limit midpoint of +0.5 mil to nominal thickness.

The reduction in the difference between maximum and minimum thickness produced by abrasive flow machining, is indicated by the reduction in the standard deviation of thickness from 1.69 mils for the "as milled" condition to 1.45 mils for the abrasive flow machined condition.

Finished airfoil thicknesses, for $\pm 2$ standard deviations, fall essentially within design limits of +4 to -3 mils. Thicknesses for $\pm$ 3 standard deviations exceed the 7 mil range of design limits by about 2 mils.

TABLE 33

GEOMETRY OF AIRFOILS AS MILLED ON STAGE 1 BLISK FOR ENGINE TESTING

| Airfoil Number | Section | Contour Deviation Spread (mils) | | Thickness Deviation (mils) | | | Chord Deviation (mils) |
|---|---|---|---|---|---|---|---|
| | | Concave | Convex | Max | Min | Avg | |
| 1 | B | 1.9 | 2.5 | + 9.8 | +2.8 | +5.4 | +.007 |
| | D | .3 | .9 | + 2.5 | + .6 | + .009 | +.009 |
| | F | .8 | 2.1 | + 1.9 | + .6 | +1.3 | +.008 |
| | H | 1.2 | 1.7 | + 1.4 | 0 | + .5 | +.006 |
| 20 | B | 1.3 | 2.1 | +10.6 | +2.6 | +6.3 | +.008 |
| | D | .9 | .8 | + 2.4 | + .7 | +1.3 | +.009 |
| | F | 1.4 | 1.1 | + 1.8 | +0 | + .6 | +.009 |
| | H | 1.6 | 2.6 | + 0 | -1.3 | + .5 | +.006 |
| 11 | B | 1.2 | 3.0 | + 9.6 | +3.9 | +6.1 | - - - |
| | D | 1.2 | .7 | + 4.4 | +2.7 | +3.4 | +.009 |
| | F | 1.5 | .9 | + 6.0 | +3.4 | +4.6 | +.009 |
| | H | 2.1 | .5 | + 7.2 | -4.5 | +5.7 | +.009 |
| 9 | B | 1.6 | 3.3 | + 6.5 | +2.6 | +4.1 | +.006 |
| | D | .9 | .4 | + 3.1 | +2.9 | +1.7 | +.007 |
| | F | 1.8 | .6 | + 3.7 | + .9 | +2.1 | +.007 |
| | H | 3.1 | 1.0 | + 3.9 | +1.2 | +2.3 | +.007 |
| 6 | B | .6 | 3.9 | + 9.1 | +3.1 | +5.2 | +.007 |
| | H | .9 | 1.2 | + 2.8 | + .8 | +1.6 | +.007 |
| 5 | B | 2.9 | 2.7 | + 7.6 | +3.5 | +5.4 | - - - |
| | H | 1.5 | .9 | + 3.5 | 0 | +1.3 | +.007 |
| 4 | B | 1.3 | 2.4 | + 9.1 | +2.4 | +5.3 | +.008 |
| | H | .6 | 1.7 | + 2.7 | 1.0 | +1.9 | +.008 |

NOTES:

Deviations are from design nominal.
Allowable limits are:

Contour: ±1.5 mils (3 total).
Thickness: +4; -3 mils (7 total).
Chord: +5; -9 mils (14 total).

TABLE 34

GEOMETRY OF AIRFOILS AFTER AFM OF STAGE 1 BLISK FOR ENGINE TESTING

| Airfoil Number | Section | Contour Deviation Spread (mils) | | Thickness Deviation (mils) | | | Chord Deviation (mils) |
|---|---|---|---|---|---|---|---|
| | | Concave | Convex | Max | Min | Avg | |
| 1 | B | 1.3 | 2.4 | + 7.2 | +0.9 | +3.9 | + 5.0 |
| | D | 0.9 | 0.6 | + 2.2 | +0.9 | +1.5 | 0 |
| | F | 1.2 | 1.2 | + 0.6 | 0 | +0.2 | -10.0 |
| | H | 1.5 | 1.4 | + 0.9 | 0.9 | +0.1 | -11.0 |
| 20 | B | 0.9 | 1.7 | + 9.4 | +1.1 | +4.8 | + 6.0 |
| | D | 0.7 | 0.1 | + 2.1 | 0 | +1.1 | + 4.0 |
| | F | 0.9 | 1.4 | + 0.6 | -1.0 | -0.2 | - 3.0 |
| | H | 0.9 | 2.0 | + 0.5 | -3.1 | -0.9 | -11.0 |
| 11 | B | 0.9 | 2.9 | + 7.2 | +2.8 | +4.4 | - - - |
| | D | 1.4 | 0.5 | + 3.1 | +1.7 | +2.4 | + 5.0 |
| | F | 1.3 | 0.5 | + 3.7 | +1.8 | +2.7 | + 5.0 |
| | H | 1.7 | 0.6 | + 6.2 | -3.2 | +4.6 | + 2.0 |
| 9 | B | 1.1 | 3.0 | + 6.5 | +1.8 | +3.3 | + 5.0 |
| | D | 0.8 | 0.9 | + 1.9 | +0.5 | +1.2 | + 4.0 |
| | F | 1.7 | 0.8 | + 1.3 | 0 | +0.5 | + 1.0 |
| | H | 2.9 | 1.1 | + 2.1 | 0 | +0.9 | - 2.0 |
| 6 | B | 0.8 | 2.8 | + 8.3 | +1.5 | +4.0 | - - - |
| | H | 0.8 | 0.7 | + 2.2 | 0 | +0.7 | - 2.0 |
| 5 | B | 1.4 | 1.9 | + 7.3 | +1.3 | +4.4 | + 5.0 |
| | H | 1.7 | 0.7 | + 1.4 | 0 | +0.6 | - 1.0 |
| 4 | B | 0.9 | 0.9 | + 8.1 | +1.2 | +4.4 | +.6.0 |
| | H | 0.4 | 1.0 | + 2.3 | 0 | +0.9 | - 2.0 |

NOTES:

Deviations are from design nominal.
Allowable limits are:
Contour: ±1.5 mils (3 total).
Thickness: +4; -3 mils (7 total).
Chord: +7; -9 mils (16 total).
Chord length could not be measured at two locations where numerical data are not shown, due to fixturing interference.
Data obtained from measurements like those in Figure 132 (pg 240).

TABLE 35
PLATFORM FLOW PATH CONTOUR AS MILLED ON STAGE 1 BLISK FOR ENGINE TESTING

| Platform Between Airfoils | Contour Deviation (inch) | |
|---|---|---|
| | Max | Min |
| 1-20 | .0033 | .0008 |
| 1-3 | .0041 | .0022 |
| 19-20 | .0062 | .0030 |
| 10-11 | .0015 | .0001 |
| 11-12 | .0022 | .0001 |
| 8-9 | .0015 | .0003 |
| 9-10 | .0008 | .0001 |

NOTES:

Deviations are from design nominal.
Design tolerance $\pm 0.004$ inch.

TABLE 36
PLATFORM FLOW PATH CONTOUR AS AFTER AFM ON STAGE 1 BLISK FOR ENGINE TESTING

| Platform Between Airfoils | Contour Deviation (inch) | |
|---|---|---|
| | Max | Min |
| 1-20 | .0033 | .0008 |
| 1-3 | .0041 | .0022 |
| 19-20 | .0062 | .0030 |
| 10-11 | .0003 | -.0015 |
| 11-12 | .0022 | -.0007 |
| 8-9 | .0004 | -.0015 |
| 9-10 | .0007 | -.0008 |

NOTES:

Deviations are from design nominal.
Design tolerance $\pm 0.004$ inch.

LEGEND

Uncut Metal
Milled Pocket
Cerro Filled

NC Program Time (min.)
Airfoil Rough -- 38
Airfoil Finish -- 31
Platform Finish-- 43

Number of Cutters Used
Airfoil Rough ----- 10
Airfoil Finish ---- 10
Platform Finish --- 3

STEP 1
Cut 10 pockets; each rough and finish milled, then all filled with Cerro matrix.

STEP 2
Cut 5 pockets; each rough and finish milled.

STEP 3
Cut 5 pockets; each rough and finish milled.

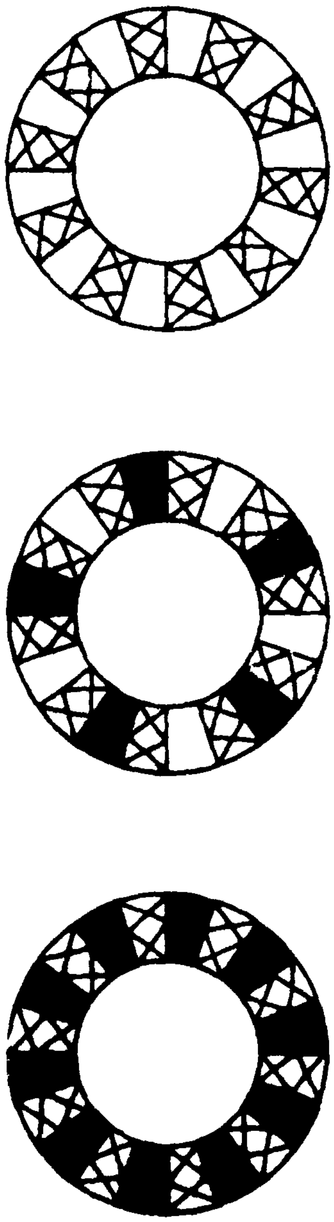


Figure 127. Procedure for Milling Airfoils and Platforms on Stage 1 Blisk for Engine Testing.

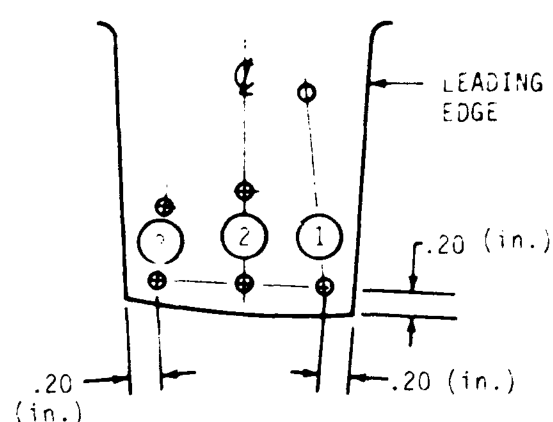
T700 BLISK DEVELOPMENT INSPECTION - AIRFOIL SURFACE ROUGHNESS REPORT

STAGE: 1 SERIAL NO. WYM 78114 INSP BY. [illegible]

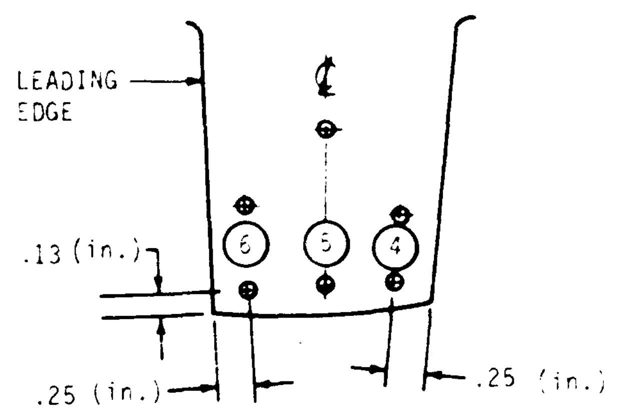
DATE: 10-29-77

SET UP AND INSPECT PER WI #PJL-72977 USING-BENDIX MICROCORDER

CONVEX SIDE: AS MILLED
(Trace in Approx Location Shown)




CONCAVE SIDE: AS MILLED
(Trace in Approx Location Shown)




| Blade No. | Sta. No. | Table Tilt Angle (Deg) | Length of Stroke (in.) | Record Ra (Average) ($\mu$ in. AA) | Sta. No. | Table Tilt Angle (Deg) | Length of Stroke (in.) | Record Ra (Average) ($\mu$ in. AA) | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| 9 | 1 | 31 | 7/8 | 51 | 4 | 31 | 3/8 | 55 | |
| | 2 | 31 | 7/16 | 45 | 5 | 34 | 5/8 | 63 | |
| | 3 | 38 | 5/16 | 56 | 6 | 32 | 1/2 | 59 | |
| | | | | | | | | | |
| 11 | 1 | | | 63 | 4 | | | 61 | |
| | 2 | | | 39 | 5 | | | 45 | |
| | 3 | | | 51 | 6 | | | 66 | |
| | | | | | | | | | |
| 20 | 1 | | | 61 | 4 | | | 36 | |
| | 2 | | | 40 | 5 | | | 45 | |
| | 3 | | | 53 | 6 | | | 72 | |
| | | | | | | | | | |

Figure 128. Typical Surface Roughness of Airfoils as Milled on Stage 1 Blisk for Engine Testing.

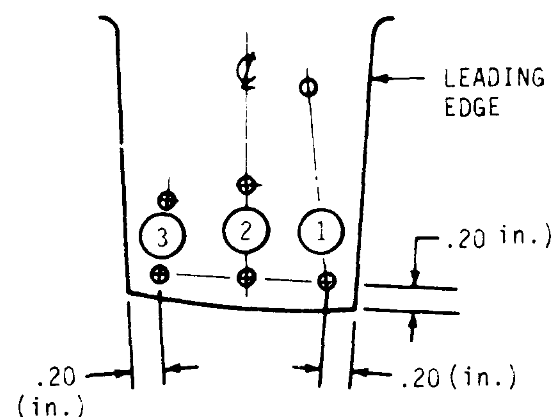
T700 BLISK DEVELOPMENT INSPECTION - AIRFOIL SURFACE ROUGHNESS REPORT

STAGE: 1 SERIAL NO. WYM 78114 INSP BY: [illegible]

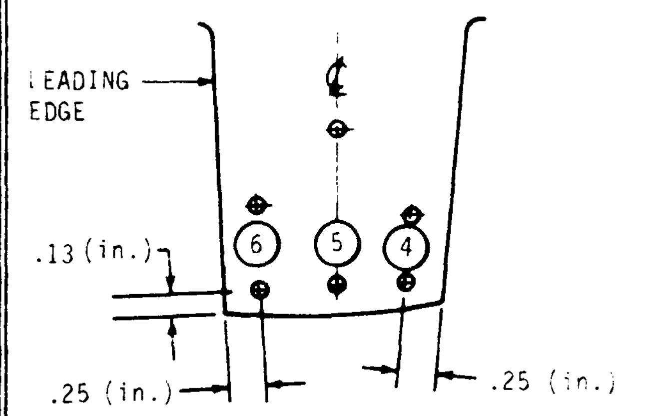
DATE: 11-1-77

SET UP AND INSPECT PER WI #RJL-72977 USING-BENDIX MICROCORDER

CONVEX SIDE: AFTER AFM
(Trace in Approx Location Shown)




CONCAVE SIDE: AFTER AFM
(Trace in Approx Location Shown)




| Blade No. | Sta. No. | Table Tilt Angle (Deg) | Length of Stroke (in.) | Record Ra (Average) ($\mu$ in. AA) | Sta. No. | Table Tilt Angle (Deg) | Length of Stroke (in.) | Record Ra (Average) ($\mu$ in. AA) | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| 9 | 1 | 31 | 7/8 | 31 | 4 | 31 | 3/8 | 37 | |
| | 2 | 31 | 7/16 | 27 | 5 | 34 | 5/8 | 20 | |
| | 3 | 38 | 5/16 | 23 | 6 | 32 | 1/2 | 16 | |
| | | | | | | | | | |
| 11 | 1 | | | 29 | 4 | | | 20 | |
| | 2 | | | 26 | 5 | | | 21 | |
| | 3 | | | 28 | 6 | | | 32 | |
| | | | | | | | | | |
| 20 | 1 | | | 20 | 4 | | | 17 | |
| | 2 | | | 16 | 5 | | | 29 | |
| | 3 | | | 23 | 6 | | | 31 | |
| | | | | | | | | | |

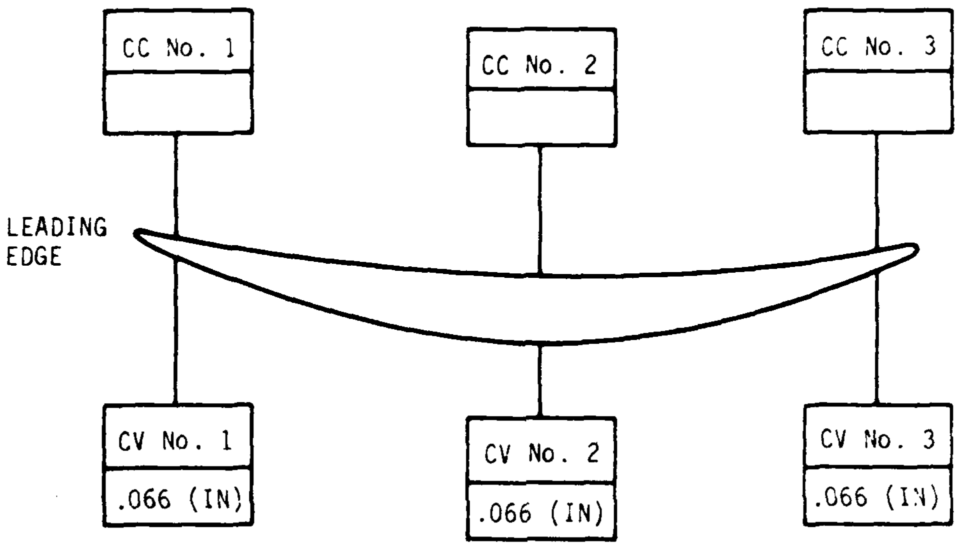
Figure 129. Typical Surface Roughness Airfoils After AFM of Stage 1 Blisk for Engine Testing.

Ref: DEV QCWI #RJL-615.77

T700 BLISK AIRFOIL DEVELOPMENT

INSPECTION LOG SHEET

ROOT RADII MEASUREMENT - Record from 20X Comparator.




Part No. ENGINE TEST No. 1 Ser. No. WYM 78114

Airfoil No. 10

Insp by: J. SHANAHAN

Date 11/2/77

| RADII LIMITS (IN) | | |
|---|---|---|
| Dwg No. | Description | Root Radii ($\pm$.010 in) |
| 6032T26 | Stage 1 Blisk | .060 |
| 6038T08<br>6038T09 | Stages 2 thru 5 Blisks | .050 |

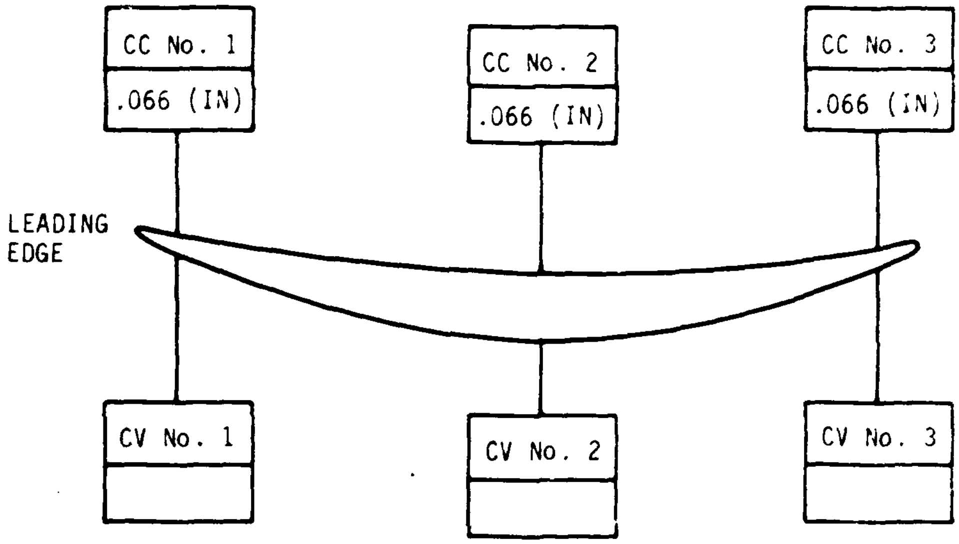
Figure 130. (Sheet 1 of 2). Typical Fillet Radius As-Milled on Stage 1 Blisk for Engine Testing.

Ref: DEV QCWI #RQL-615.77

T700 BLISK AIRFOIL DEVELOPMENT

INSPECTION LOG SHEET

ROOT RADII MEASUREMENT - Record from 20X Comparator.




Part No. ENGINE TEST NO. 1    Ser. No. WYM 78114

Airfoil No. 12

Insp by: J. SHANAHAN

Date 11/2/77

| RADII LIMITS (IN) | | |
|---|---|---|
| Dwg No. | Description | Root Radii ($\pm$.010 in) |
| 6032T26 | Stage 1 Blisk | .060 |
| 6038T08<br>6038T09 | Stages 2 thru 5 Blisks | .050 |

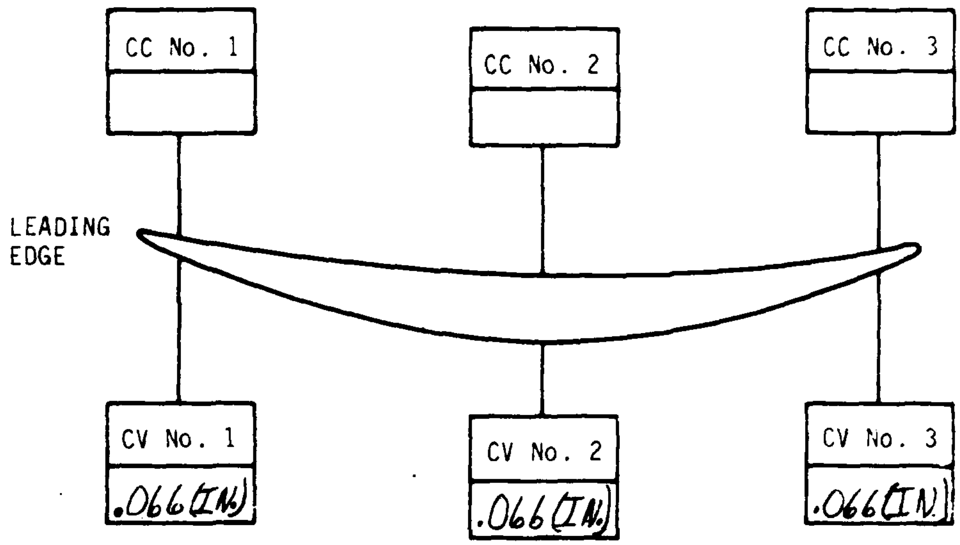
Figure 130. (Sheet 2 of 2). Typical Fillet Radius As-Milled on Stage 1 Blisk for Engine Testing.

Ref: DEV QCWI #RJL-615.77

T700 BLISK AIRFOIL DEVELOPMENT

INSPECTION LOG SHEET

ROOT RADII MEASUREMENT - Record from 20X Comparator




Part No. ENGINE TEST NO.1 Ser. No. WYM 78114

Airfoil No. 10

Insp by: J.SHANAHAN

Date 11/2/77

| RADII LIMITS (IN) | | |
|---|---|---|
| Dwg No. | Description | Root Radii ($\pm$.010 in) |
| 6032T26 | Stage 1 Blisk | .060 |
| 6038T08<br>6038T09 | Stages 2 thru 5 Blisks | .050 |

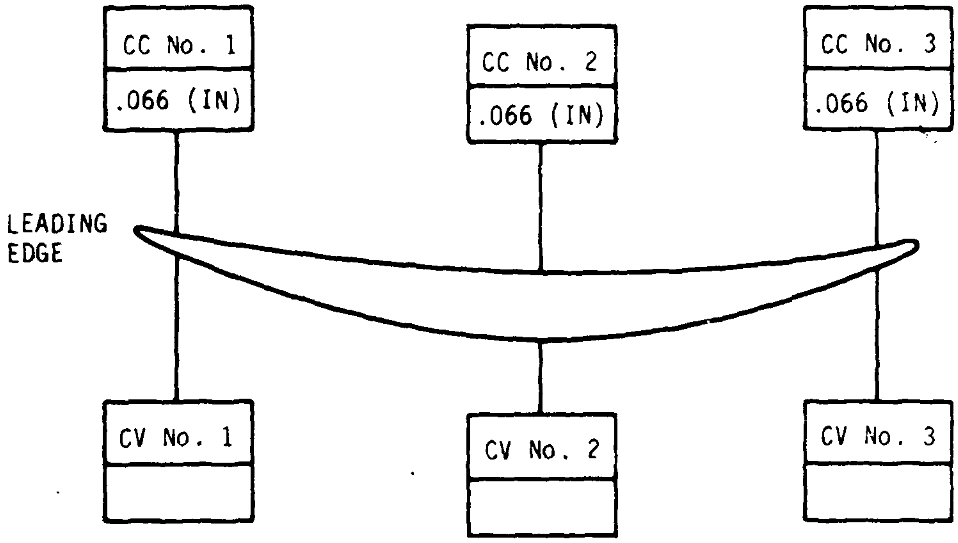
Figure 131.(Sheet 1 of 2). Typical Fillet Radius After AFM of Stage 1 Blisk for Engine Testing.

Ref: DEV QCWI #RJL-615.77

T700 BLISK AIRFOIL DEVELOPMENT

INSPECTION LOG SHEET

ROOT RADII MEASUREMENT - Record from 20X Comparator.




Part No. ENGINE TEST NO. 1 Ser. No. WYM 78114

Airfoil No. 12

Insp by: J. SHANAHAN

Date 11/2/77

| RADII LIMITS (IN) | | |
|---|---|---|
| Dwg No. | Description | Root Radii (±.010 in) |
| 6032T26 | Stage 1 Blisk | .060 |
| 6038T08<br>6038T09 | Stages 2 thru 5 Blisks | .050 |

Figure 131 (Sheet 2 of 2). Typical Fillet Radius After AFM of Stage 1 Blisk for Engine Testing.

PART NO. TEST ENGINE No 1 SER. NO. WXM 78 114 STAGE 1

OBSERVER: W W [illegible] DATE: 11-4-77 CHORD (DWG)

AF NO. 11

SECT. F-F

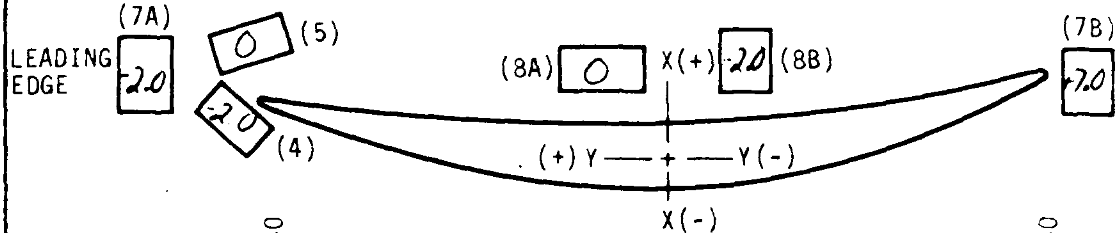
AFTER AFM

| SECT | DIM |
|---|---|
| F-F | 1.5137 |

LEADING EDGE

-0°9'

| | .040 | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | .040 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (3) THICKNESS | +3.4 | | +3.7 | | +3.1 | | +1.8 | | +1.8 | | +2.5 | | +2.0 | | +3.1 | | +2.8 | 2.7 | AVERAGE |
| CONCAVE (1) | 0 | | 0 | | -.2 | | -.7 | | -1.3 | | -1.3 | | -1.3 | | -.9 | | -.1 | 1.3 | CONTOUR SPREAD |




| | .040 | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | .040 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CONVEX (2) | 0 | | 0 | | 0 | | 0 | | 0 | | +.5 | | +.5 | | +.5 | | .4 | .5 | CONTOUR (SPREAD) |

COMMENTS: ALL VALUES ARE DEVIATION FROM NOMINAL AND

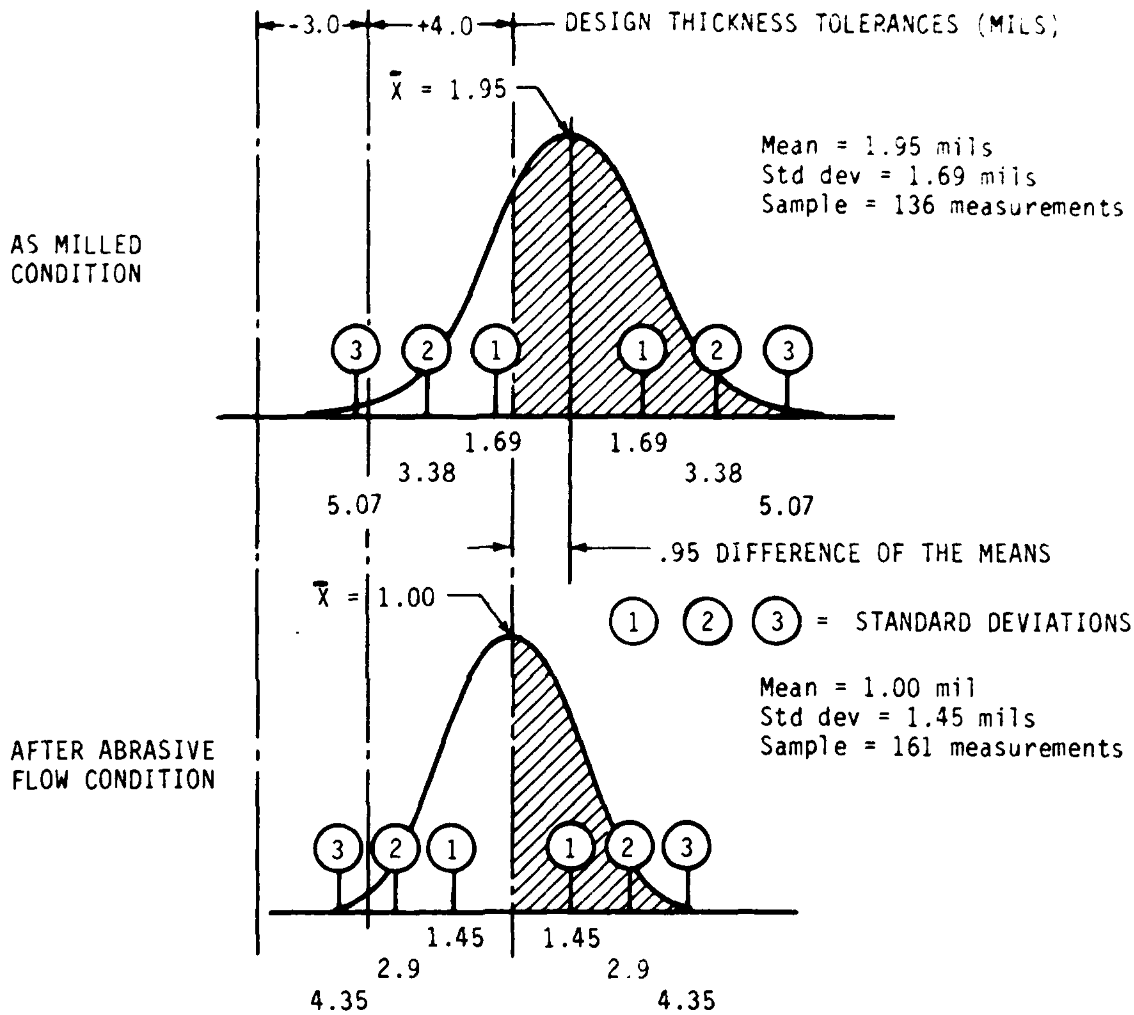
SET UP AND INSPECT PER: ARE RECORDED X 1000 I.E. 7.2 = .0072 IN

| TRACE DATA - RECORD THE FOLLOWING | ROTARY TABLE POSITION (BLADE CENTRAL) |
|---|---|
| | DRAWING: ACTUAL: |

RECORD ALL DATA FROM COMPARATOR MEASUREMENTS AS FOLLOWS:

| DRAWING LIMITS | ITEM NO. | DESCRIPTION (ALL NUMBERS ARE INCHES EXCEPT AS NOTED) |
|---|---|---|
| ±.0015 | (1) | Contour Deviation - Concave Side |
| ±.0015 | (2) | Contour Deviation - Convex Side |
| +.004 -.003 | (3) | Thickness - Deviation from Nominal (+ or -) |
| ±.008 | (4) | Tip Location - Deviation from Nominal - Convex Side |
| ±.005 B-B) | (5) | Tip Location - Deviation from Nominal - Concave Side |
| +.007/-.009 | (6) | Chord - Full (Deviation from Nominal)(By Indicator) = ±.005 |
| N/A | (7A) | Chord from Center to Leading Edge |
| N/A | (7B) | Chord from Center to Trailing Edge |
| ±.002±.005 master central | (8A) | Y-Stacking Axis Shift (+ ◄—► -) |
| ±.002 master | (8B) | X-Stacking Axis Shift (↑ +) (↓ -) |
| $\pm .0^{\circ}45'$ | (9) | Warp Angle - Record at Best Fit: -0°4' |
| ±.005 | (10) | Blade - Circumference True Position (At Master Section Only) (Deviation from Nominal) |

Figure 132. Geometry of Thickest Airfoil After AFM of Stage 1 Blisk for Engine Testing.




NOTE: Thickness measurements for Section BB were not included and have substantially greater standard deviations.

Statistical Definitions:
95.4% of the airfoil thickness measurements are within $\pm2$ standard deviation and 99.7% are within $\pm3$ standard deviation.

Blisk:
Stage 1 Serial No. 78114, Sections DD, FF, HH.

Figure 133. Statistical Analysis of Thickness Measurements Taken From Airfoils Milled With Development Machine on Stage 1 Blisk for Engine Testing.

PROCESS CAPABILITY

STAGE 2 BLISK

STAGE 2 BLISK PROCESS CAPABILITY

Airfoils were machined on the first Stage 2 blisk produced under this program with the development machine. This blisk was produced for engine testing. No difficulties were experienced with NC programs or metal cutting in the course of milling airfoils and platforms. A total of only eight rough milling cutters, two airfoil finish milling cutters, and one platform finish milling cutters were used; no cutter breakage was experienced. Finishing was done with the production AFM machine and fixture without difficulty.

Milling was performed in the following sequence: every other pocket between airfoils was rough milled; then the sides of these pockets were finished milled with the platform finish milling cutter. Next, the pockets were filled with a low metling temperature alloy. The same milling sequence was used for the remaining pockets to produce finished airfoils and platforms.

It was found that heating of the development machine while finish milling a series of platforms at 7500 rpm, caused the end of the cutter to move toward the center line of the blisk a distance of almost three mils. A procedure was developed to prevent this from affecting the platform contour. It consisted of a warm-up period of 1/2 hour at cutting speed, after which the cutter length was set just prior to that part of the finishing operation which produced the final platform surface. This setting was checked each time this part of the operation was performed on a different platform. Warm-up was needed only after the machine had been shut down overnight.

Milling sequence and parameters are given in Figure 134 (pg 250) and Table 37 (pg 244). Abrasive flow machining parameters are given in Table 38 (pg 245). Typical results of measurements of airfoil geometry are given in Tables 39-40 (pgs 246-247) and Figure 135 (pg 251). The thickness of the airfoil section just above the platform was programmed to be 6 mils above other sections, or 2 mils less that for the Stage 1 blisk. The spread and average of thickness deviations for this section indicated that an opportunity existed to futher reduce programmed thickness, to reduce deviations above maximum design limits.

Airfoil surface roughness data are given in Figure 136 (pg 252) and leading edge contour data in Table 41 (pg 248).

Platform contour deviations exceeded design limits, after AFM, on some odd-numbered platforms which were milled prior to the development of a suitable procedure to minimize effects of milling machine spindle dimensional changes caused by heating at 7500 rpm. Contours for even-numbered platforms, which were all milled with the procedure, were well within design limits. Data are given in Table 42 (pg 249).

No difficulties were encountered with milling or AFM finishing.

TABLE 37

CUTTING PARAMETERS USED FOR MILLING AIRFOILS AND PLATFORMS WITH DEVELOPMENT MACHINE ON STAGE 2 FOR BLISK FOR ENGINE TESTING

| Operation | Cutting Speed (sft/min) | Lineal Feed (inch/min) | Down feed (inch/pass) | Depth of Cut (inch) | Cutter Extension (inch) | Cutter Diam. (inch) | No. Flutes | Cutter Geometry: Helix Angle (deg) | Cutter Geometry: Rake Angle (deg) | Cutter Geometry: Relief Angle (deg) | Cutter Geometry: Corner Radius (Inch) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Airfoil Rough Contour Milling | 184 | 2.4 | .120 | .312 Step Cut | 1.5 | .312 | 6 | 30 | 0 | 6 | .060 |
| Airfoil Finish Contour Milling | 147 | 15 | .010 | .020 | 1.5 | .312 | 12 | 30 | 30 Neg | 45 | .156 |
| Platform Finish Contour Milling | 196 | 15 | .010 | .010 | 1.7 | .100 | 12 | 30 | 30 Neg | 45 | .050 |

**NOTES:**

Part - Stage 2 Blisk SN 80200-00065-22463
Part Material - AM355
Part Hardness - 36RC
Cutter Material - Carbide Grade 883

TABLE 38

AFM PARAMETERS USED TO FINISH STAGE 2 BLISK AIRFOILS AND PLATFORMS MILLED ON DEVELOPMENT MACHINE FOR ENGINE TESTING

AFM PARAMETERS

| | | |
|---|---|---|
| Part | - | Stage 2 AM355 Blisk SN80200-00065-22463 |
| Machine | - | Dynetics Production - HL60CF-830 |
| Tooling | - | Production Tooling |
| Media | - | D080-20A(61) - 36A(73) - 700(40) |
| Media Temperature | | 98°F Avg |
| Media Pressure | - | 150 psi |
| Total Cycles | - | 55 |
| Total Time | - | 40 minutes |

NOTE:

This blisk was abrasive flowed in two operations. First operation was for 40 cycles and after chord and surface finish checks were made, a second operation of 15 cycles was applied.

TABLE 39
GEOMETRY OF AIRFOILS AS MILLED WITH DEVELOPMENT MACHINE ON STAGE 2 BLISK FOR ENGINE TESTING

| Airfoil Number | Section | Contour Deviation Spread (mils) | | Thickness Deviation (mils) | | | Chord Deviation (mils) |
|---|---|---|---|---|---|---|---|
| | | Concave | Convex | Max | Min | Avg | |
| 6 | B | 1.2 | 1.1 | +12.0 | +9.5 | +9.8 | +7.0 |
| | D | 1.7 | 0.8 | + 5.8 | +3.1 | +4.4 | +8.0 |
| | F | 1.7 | 0.7 | + 6.5 | +3.0 | +4.3 | +7.0 |
| | H | 2.5 | 1.3 | + 4.7 | +2.9 | +3.7 | +7.4 |
| 11 | B | 0.6 | 0.8 | + 8.5 | +6.9 | +7.9 | +9.4 |
| | D | 0.9 | 1.2 | + 4.3 | +2.1 | +3.0 | +7.9 |
| | F | 1.0 | 0.9 | + 5.1 | +3.1 | +3.7 | +8.5 |
| | H | 0.6 | 1.1 | + 3.7 | +2.4 | +2.8 | +8.4 |
| 16 | B | 1.3 | 0.2 | +11.2 | +9.1 | +10.5 | +7.9 |
| | D | 1.1 | 1.1 | + 6.3 | +3.3 | + 4.5 | +5.9 |
| | F | 1.3 | 0.7 | + 7.3 | +4.6 | + 5.6 | +5.0 |
| | H | 1.2 | 1.0 | + 6.5 | +4.1 | + 5.0 | +6.9 |
| 22 | B | 1.3 | 1.3 | +11.4 | +9.0 | +10.4 | +5.4 |
| | D | 1.3 | 0.8 | + 5.6 | +2.4 | + 3.8 | +5.4 |
| | F | 1.2 | 0.7 | + 5.8 | +2.8 | + 4.2 | +5.5 |
| | H | 0.9 | 1.2 | + 6.0 | +3.1 | + 4.3 | +5.4 |

**NOTES:**

Deviations are from design nominal.
Allowable limits are:
- Contour: $\pm$1.5 mils (3 total).
- Thickness: +4; -3 mils (7 total).
- Chord: +5; -9 mils (14 total).

Data were obtained from measurements like those in Figure 136 (pg 250).

TABLE 40

GEOMETRY AFTER AFM OF AIRFOILS MILLED WITH
DEVELOPMENT MACHINE ON STAGE 2 BLISK FOR ENGINE TESTING

| Airfoil Number | Section | Contour Deviation Spread (mils) | | Thickness Deviation (mils) | | | Chord Deviation (mils) |
|---|---|---|---|---|---|---|---|
| | | Concave | Convex | Max | Min | Avg | |
| 3 | B | 1.1 | 0.6 | + 7.7 | +6.5 | +7.0 | +4.4 |
| | D | 0.5 | 0.9 | + 3.1 | +0.7 | +1.8 | +3.0 |
| | F | 0.2 | 1.3 | + 2.7 | +0.2 | +1.2 | +1.0 |
| | H | 1.1 | 2.2 | + 2.7 | +0.1 | +1.3 | -2.0 |
| 6 | B | 1.3 | 0.8 | +10.7 | +8.5 | +9.7 | +8.0 |
| | D | 0.6 | 0.4 | + 3.7 | +1.3 | +2.2 | +3.0 |
| | F | 1.3 | 1.0 | + 3.3 | +1.4 | +2.2 | +0.0 |
| | H | 1.8 | 0.8 | + 3.2 | +1.9 | +2.5 | -2.0 |
| 11 | B | 0.8 | 1.3 | + 8.0 | +5.5 | + 6.5 | +5.0 |
| | D | 0.8 | 0.3 | + 3.1 | +0.5 | + 1.7 | +2.0 |
| | F | 0.6 | 0.9 | + 2.8 | +0.8 | + 1.6 | +1.0 |
| | H | 0.4 | 0.6 | + 2.9 | +1.1 | + 1.9 | -3.0 |
| 14 | B | 2.0 | 0.8 | +11.8 | +7.7 | + 9.8 | +4.0 |
| | D | 0.9 | 0.6 | + 3.8 | +1.7 | + 2.7 | +3.0 |
| | F | 0.9 | 0.2 | + 4.3 | +2.4 | + 3.3 | +1.0 |
| | H | 0.6 | 0.5 | + 4.1 | +2.8 | + 3.5 | -2.0 |
| 16 | B | 1.3 | 0.7 | +10.2 | +7.7 | + 9.6 | -6.0 |
| | D | 0.9 | 1.5 | + 4.4 | +2.0 | + 3.0 | -1.0 |
| | F | 0.5 | 0.7 | + 4.6 | +2.9 | + 3.8 | 0.0 |
| | H | 1.2 | 0.4 | + 4.7 | +3.1 | + 3.9 | -1.0 |
| 22 | B | 0.8 | 0.7 | +10.9 | +8.9 | + 9.7 | +1.4 |
| | D | 0.8 | 0.9 | + 2.7 | +1.3 | + 2.0 | +1.0 |
| | F | 1.1 | 1.1 | + 4.4 | +2.2 | + 3.0 | -4.0 |
| | H | 0.3 | 1.7 | + 3.8 | +1.7 | + 2.4 | -9.0 |

**NOTES:**

Deviations are from design nominal.
Allowable limits are:
Contour: ±1.5 mils (3 total).
Thickness: +4; -3 mils (7 total).
Chord: +7; -9 mils (14 total).
Data were obtained from measurements like those in Figure 136 (pg 250).

TABLE 41
LEADING EDGE CONTOURS AFTER AFM OR AIRFOILS MILLED WITH DEVELOPMENT MACHINE ON STAGE 2 BLISK FOR ENGINE TESTING

| | SECTION | | | |
|---|---|---|---|---|
| AIRFOIL | BB | DD | FF | HH |
| 3 | Acceptable | Acceptable | Acceptable | Acceptable |
| 6 | Acceptable | Acceptable | Acceptable | Acceptable |
| 11 | Acceptable | Acceptable | Acceptable | Acceptable |
| 14 | Acceptable | Acceptable | Acceptable | Acceptable |
| 16 | Acceptable | Acceptable | Acceptable | Acceptable |
| 22 | Acceptable | Acceptable | Acceptable | Acceptable |

Contours compared with master at approximately 30 magnifications using light sectioning equipment.

TABLE 42
CONTOURS AFTER BENCHING AND AFM OF PLATFORMS MILLED WITH DEVELOPMENT MACHINE ON STAGE 2 BLISK FOR ENGINE TESTING

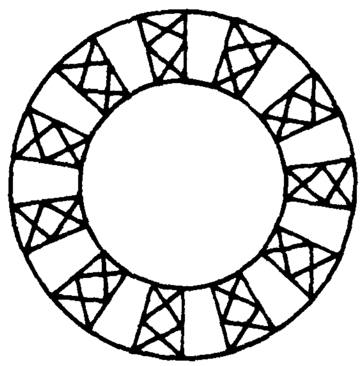
| Platform Number | Inspection Location: Location Number | Inspection Location: Distance From TE Face (in) | Platform Contour Deviation from the Nominal Radius (mils) |
|---|---|---|---|
| 1 | 1 | 1.3125 | +2.2 |
| | 2 | 1.1251 | +2.1 |
| | 3 | 0.5315 | +1.3 |
| 2 | 1 | 1.3125 | -0.9 |
| | 2 | 1.1251 | -0.5 |
| | 3 | 0.5315 | -1.2 |
| 3 | 1 | 1.3125 | +0.9 |
| | 2 | 1.1251 | +1.5 |
| | 3 | 0.5315 | +0.3 |
| 4 | 1 | 1.3125 | -0.1 |
| | 2 | 1.1251 | +0.3 |
| | 3 | 0.5315 | -0.9 |
| 5 | 1 | 1.3125 | +2.8 |
| | 2 | 1.1251 | +3.4 |
| | 3 | 0.5315 | +1.5 |
| 6 | 1 | 1.3125 | -0.7 |
| | 2 | 1.1251 | 0.0 |
| | 3 | 0.5315 | -1.6 |
| 7 | 1 | 1.3125 | +2.2 |
| | 2 | 1.1251 | +3.0 |
| | 3 | 0.5315 | -1.1 |
| 8 | 1 | 1.3125 | +0.1 |
| | 2 | 1.1251 | +0.8 |
| | 3 | 0.5315 | -1.5 |
| 9 | 1 | 1.3125 | +3.4 |
| | 2 | 1.1251 | +4.1 |
| | 3 | 0.5315 | +3.6 |

Legend
Uncut Metal
Milled Pocket
Cerro Filled

NC Program Time (min)
Airfoil Rough----- 30
Airfoil Finish---- 60
Platform Finish--- 43

Number of Cutters Used
Airfoil Rough---- 5
Airfoil Finish--- 5
Platform Finish-- 1

Step 1
Cut 11 pockets total; roughed 11 pockets, then finished 11 pockets with airfoil finish cutter, then finished 11 platforms with platform finish cutter. Filled all pockets with Cerro matrix.



Step 2
Cut 11 pockets total; roughed 11 pockets, then finished 11 pockets with airfoil finish cutter, then finish 11 platforms with platform finish cutter.

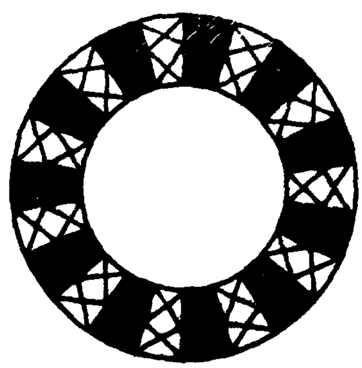
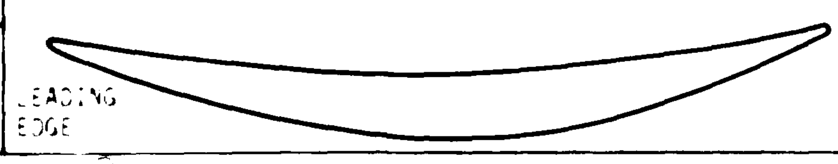


Figure 134. Procedure for Milling Airfoils and Platforms With Development Machine on Stage 2 Blisk for Engine Testing.

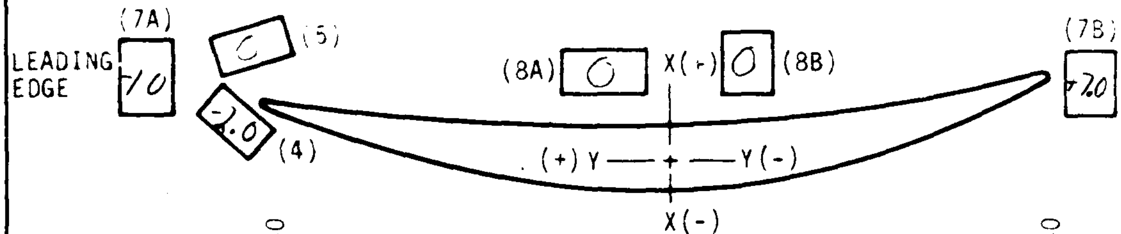
| PART NO. 203 F 27 | SER. NO. 3 0 2 0 0 | STAGE 2 |
|---|---|---|
| OBSERVER: W W A | DATE: 2-14-78 | CHORD DWG. |

AF NO. 11
SECT. F F
AFTER AFM




| SECT | DIM |
|---|---|
| F F | 1.1590 |

| | .040 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | .040 | |
|---|---|---|---|---|---|---|---|---|---|---|
| (3) THICKNESS | +1.7 | +1.3 | +.8 | +1.0 | +1.0 | +1.3 | +2.2 | +2.8 | +2.4 | +1.61 AVERAGE |
| CONCAVE (1) | 0 | -.1 | -.6 | -.6 | -.6 | -.6 | -.6 | -.6 | -.4 | .6 CONTOUR SPREAD |




| 0° 0' | .040 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | .040 | |
|---|---|---|---|---|---|---|---|---|---|---|
| CONVEX (2) | 0 | -.5 | -.6 | -.8 | -.8 | -.9 | -.6 | -.6 | -.2 | .9 CONTOUR SPREAD |

COMMENTS ALL VALUES ARE DEVIATION FROM NOMINAL AND ARE RECORDED X 1000 I.E. 1.2 = .0012

SET UP AND INSPECT PER

| TRACE DATA - RECORD THE FOLLOWING | ROTARY TABLE POSITION (BLADE CENTRAL) |
|---|---|
| | DRAWING: ACTUAL: |

RECORD ALL DATA FROM COMPARATOR MEASUREMENTS AS FOLLOWS:

| DRAWING LIMITS | ITEM NO. | DESCRIPTION (ALL NUMBERS ARE INCHES EXCEPT AS NOTED) |
|---|---|---|
| ±.0015 | (1) | Contour Deviation - Concave Side |
| ±.0015 | (2) | Contour Deviation - Convex Side |
| +.004 -.003 | (3) | Thickness - Deviation from Nominal (+ or -) |
| ±.008 | (4) | Tip Location - Deviation from Nominal - Convex Side |
| ±.005 B-B) | (5) | Tip Location - Deviation from Nominal - Concave Side |
| +.007/-.009 | (6) | Chord - Full (Deviation from Nominal)(By Indicator) = +1.0 |
| N/A | (7A) | Chord from Center to Leading Edge |
| N/A | (7B) | Chord from Center to Trailing Edge |
| ±.002±.005 master central | (8A) | Y-Stacking Axis Shift (+←→-) |
| ±.002 master | (8B) | X-Stacking Axis Shift (↑ +) (↓ -) |
| ±.0°45' | (9) | Warp Angle - Record at Best Fit: |
| ±.005 | (10) | Blade - Circumference True Position (At Master Section Only) (Deviation from Nominal) |

Figure 135. Surface Roughness After AFM of Airfoils Milled With Development Machine on Stage 2 Blisk for Engine Testing.

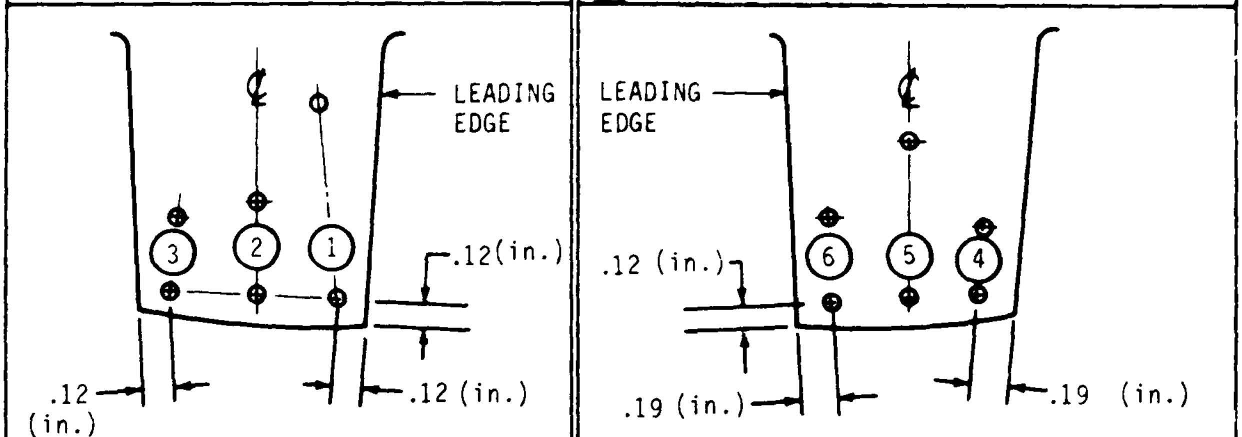
T700 BLISK DEVELOPMENT INSPECTION - AIRFOIL SURFACE ROUGHNESS REPORT

STAGE: 2 SERIAL NO. 80200 INSP BY: w w G

DATE: 2-3-78

SET UP AND INSPECT PER W1 #RJL-72977 USING-BENDIX MICROCORDER

| CONVEX SIDE: (Trace in Approx Location Shown) | CONCAVE SIDE: (Trace in Approx Location Shown) |
|---|---|




| Blade No. | Sta. No. | Table Tilt Angle (Deg) | Length of Stroke (in.) | Record Ra (Average) ($\mu$ in.AA) | Sta. No. | Table Tilt Angle (Deg) | Length of Stroke (in.) | Record Ra (Average) ($\mu$ in.AA) | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| 3 | 1 | 37 | 9/16 | 24 | 4 | 40 | 5/16 | 30 | |
| | 2 | 40 | 1/2 | 18 | 5 | 42 | 3/8 | 32 | |
| | 3 | 50 | 5/16 | 37 | 6 | 40 | 5/16 | 20 | |
| | | | | | | | | | |
| 6 | 1 | | | 16 | 4 | | | 28 | |
| | 2 | | | 17 | 5 | | | 25 | |
| | 3 | | | 32 | 6 | | | 21 | |
| | | | | | | | | | |
| 11 | 1 | | | 26 | 4 | | | 31 | |
| | 2 | | | 21 | 5 | | | 35 | |
| | 3 | | | 21 | 6 | | | 33 | |
| | | | | | | | | | |

Figure 136. Surface Roughness After AFM of Airfoils Milled With Development Machine on Stage 2 Blisk for Engine Testing.

PROCESS CAPABILITY

STAGES 3 AND 4 BLISK

## STAGES 3 AND 4 BLISK PROCESS CAPABILITY

Airfoils were milled on the first Stages 3 and 4 blisk, using the development machine, and were finished with the production AFM machine and fixture. It was produced for engine testing. The milling sequence and cutting parameters are given in Figures 137 and 138 (pgs 260-261), and Table 43 (pg 254). Abrasive flow machining parameters are given in Table 44 (pg 255). The results of airfoil geometry measurements are presented in Tables 45-46 (pgs 256-257). Typical surface roughness data are given in Figures 139 and 140 (pgs 262-263). Platform contour data are given in Tables 47-48 (pgs 258-259). Typical airfoil geometry measurements are given in Figures 141-142 (pgs 264-265). All fillets and leading edge contours were within limits.

Airfoil thickness deviations, above maximum design limits, were greater and more numerous at the section adjacent to the platform, than at other sections. This section is milled by the platform finish contour milling cutter and was programmed to be four mils thicker than those milled with the airfoil cutter, to insure that this section would not be significantly thinner than those above it, and to allow for material removal by benching.

Airfoil average thickness, produced by airfoil cutters, was only slightly greater for Stage 3 as a result of an investigation of the effects of utilizing cutters to finish a greater number of airfoils than for Stage 4.

No difficulties were encountered with milling or AFM finishing.

### Statistical Analysis of Airfoil Thickness

A statistical analysis was made of airfoil thickness measurements obtained from the first Stages 3 and 4 blisk, to evaluate process capability. Results showed that about 90% of thicknesses for all airfoils at two defined sections, not including the section closest to the platform, should be within design limits. Results also showed that over fifty percent of thicknesses for all airfoils at the section adjacent to the platform whould be within design limits.

The analysis was made with the aid of a statistical computer program, based on a normal distribution. Typical results are shown in Figure 143-146 (pgs 266-269).

While mean thicknesses were between one and three mils above the design limit mean of +0.5 mils, the means are about the best that could be chosen without increasing the percentage of thicknesses which would fall below the minimum design limit.

TABLE 43
CUTTING PARAMETERS USED FOR MILLING AIRFOILS AND PLATFORMS WITH DEVELOPMENT MACHINE ON STAGE 3 AND 4 FOR BLISK FOR ENGINE TESTING

| Operation | Cutting Speed (sft/min) | Lineal Feed (inch/min) | Down feed (inch/pass) | Depth of Cut (inch) | Cutter Extension (inch) | Cutter Diam. (inch) | No. Flutes | Cutter Geometry | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Helix Angle (deg) | Rake Angle (deg) | Relief Angle (deg) | Corner Radius (Inch) |
| Airfoil Rough Contour Milling | 123 | 2.4 | .120 | .312 | 2.0 | .312 | 6 | 30 | 0 | 6 | .060 |
| Airfoil Finish Contour Milling | 188 | 15 | .010 | .020 | 2.0 | .312 | 12 | 30 | -30 | 30 | .156 |
| Platform Finish Contour Milling | 196 | 15 | .010 | .010 | 2.2 | .100 | 12 | 30 | -30 | 30 | .050 |

NOTES:

Part - Stage 3 and 4 Blisk
Part Material - AM355
Part Hardness - 38 Rockwell C
Cutter Material - Grade 883 Carbide

TABLE 44

AFM PARAMETERS USED TO FINISH STAGES 3 AND 4 BLISK AIRFOILS AND PLATFORMS MILLED ON DEVELOPMENT MACHINE FOR ENGINE TESTING

AFM PARAMETERS

| | | |
|---|---|---|
| Part | - | Stages 3 and 4 Blisk |
| Machine | - | Dynetics Production - HL60CF-830 |
| Tooling | - | Production Tooling |
| Media | - | D070-20A(61) - 36A73) - 700(40) |
| Media Temperature | | 84°F Avg |
| Media Pressure | - | 150 psi |
| Total Cycles | - | 75 |
| Total Time | - | 58 minutes |

NOTE:

This blisk was abrasive flowed in two operations. First operation was for 45 cycles. After chord and surface finish checks were made, a second operation of 15 cycles was applied.

## TABLE 45
## GEOMETRY OF AIRFOILS AS MILLED WITH DEVELOPMENT MACHINE ON STAGE 3 BLISK FOR ENGINE TESTING

| Airfoil Number | Section | Contour Deviation Spread (mils) Concave | Convex | Thickness Deviation (mils) Max | Min | Avg | Chord Deviation (mils) |
|---|---|---|---|---|---|---|---|
| 1 | C | .9 | 3.6 | +6.5 | + .5 | +3.0 | + 2.0 |
| | E | .5 | 2.6 | +4.8 | 0 | +1.9 | - 1.5 |
| | H | .2 | 1.3 | +3.1 | +1.3 | +2.2 | + 1.5 |
| 4 | C | 1.3 | 2.3 | +5.0 | + .3 | +2.8 | + 1.0 |
| | E | 1.6 | 1.3 | +3.6 | - .9 | .4 | +10.0 |
| | H | 1.4 | .6 | +2.0 | - .8 | .2 | - 3.5 |
| 8 | C | 1.9 | 3.8 | +6.0 | + .5 | +3.3 | + 9.0 |
| | E | 1.7 | 1.7 | +4.3 | 0 | +1.2 | - 3.5 |
| | H | 1.6 | .4 | +2.4 | - .9 | + .5 | - 2.5 |
| 13 | C | .9 | 4.2 | +8.7 | + .6 | +3.7 | + 4.0 |
| | E | .6 | 3.4 | +4.7 | - .8 | 1.2 | + .5 |
| | H | 0 | 2.5 | +4.7 | +1.8 | +3.1 | + 5.5 |
| 20 | C | .2 | 3.3 | +9.2 | + .9 | +4.1 | 2.0 |
| | E | 1.2 | 3.0 | +5.5 | 0 | +2.0 | + 1.5 |
| | H | 8 | 1.2 | +5.0 | +1.4 | +2.6 | + 2.5 |
| 27 | C | 1.0 | 4.1 | +8.2 | +1.0 | +4.1 | + 7.0 |
| | E | 1.2 | 3.3 | +5.7 | 0 | +2.0 | + 3.5 |
| | H | 0 | 3.0 | +5.9 | +2.2 | +3.9 | + 6.5 |
| 28 | C | 1.6 | 4.1 | +5.4 | + .5 | +2.6 | + 5.0 |
| | E | .3 | 2.5 | +4.0 | 0 | +1.6 | - 1.5 |
| | H | 0 | 2.0 | +5.0 | +1.8 | 3.0 | + 8.5 |

**NOTES:**

Deviations are from design nominal.
Allowable limits are:
Contour: $\pm$1.5 mils (3 total).
Thickness: +4; -3 mils (7 total).
Chord: +7; -9 mils (16 total).
Data were obtained from measurements like those in Figure 139 (pg 262).

TABLE 46
GEOMETRY AFTER AFM OF AIRFOILS MILLED WITH
DEVELOPMENT MACHINE ON STAGE 2 BLISK FOR ENGINE TESTING

| Airfoil Number | Section | Contour Deviation Spread (mils) | | Thickness Deviation (mils) | | | Chord Deviation (mils) |
|---|---|---|---|---|---|---|---|
| | | Concave | Convex | Max | Min | Avg | |
| 2 | N | 1.1 | 1.3 | +5.7 | +1.9 | +3.2 | + 1.5 |
| | R | .5 | 1.1 | +3.0 | - .5 | + .8 | - 2.0 |
| | V | .7 | .7 | +2.7 | + .3 | +1.4 | - 9.5 |
| 4 | N | 1.7 | 1.5 | +5.9 | +1.0 | +3.2 | + 3.5 |
| | R | .9 | 1.3 | +2.4 | -1.7 | - .2 | - 4.0 |
| | V | .9 | .4 | +3.8 | - .9 | +1.0 | -10.5 |
| 11 | N | .4 | 2.1 | +7.2 | +2.9 | +5.0 | + 5.5 |
| | R | .2 | 1.3 | +4.0 | 0 | +1.7 | + 2.0 |
| | V | .3 | .2 | +3.3 | +1.3 | +2.2 | - 3.5 |
| 16 | N | .5 | 1.6 | +6.7 | +2.9 | +3.7 | + 4.5 |
| | R | 1.0 | .9 | +4.9 | + .4 | +2.1 | + 3.0 |
| | V | 1.5 | .3 | +3.8 | +1.0 | +2.3 | - 2.5 |
| 19 | N | .5 | 1.1 | +7.6 | +3.7 | +4.9 | + 6.5 |
| | R | 1.0 | .6 | +5.2 | + .6 | +2.7 | + 2.0 |
| | V | 1.2 | 1.7 | +5.7 | +2.2 | +3.9 | + .5 |
| 24 | N | 1.3 | 1.5 | +6.4 | +2.8 | +4.1 | + 7.5 |
| | R | .9 | 1.0 | +5.3 | 0 | +2.4 | + 1.0 |
| | V | .8 | .4 | +4.9 | + .9 | +2.6 | - 4.5 |
| 26 | N | 1.2 | .6 | +6.9 | +3.0 | +4.5 | + 3.5 |
| | R | 1.5 | .7 | +4.3 | - .4 | +1.9 | - 6.0 |
| | V | 1.7 | .6 | +4.6 | + .2 | +1.9 | +10.5 |

NOTES:

Deviations are from design nominal.
Allowable limits are:
    Contour: ±1.5 mils (3 total).
    Thickness: +4; -3 mils (7 total).
    Chord: +7; -9 mils (16 total).
Data were obtained from measurements like those in Figure 140 (pg 203).

TABLE 47

CONTOURS AFTER BENCHING AND AFM OF PLATFORMS MILLED WITH DEVELOPMENT MACHINE ON STAGE 3 BLISK FOR ENGINE TESTING

| Platform Number | Location Number | Distance From TE Face (in) | Platform Contour Deviation from the Nominal Radius (mils) |
|---|---|---|---|
| 1 | 4 | 1.885 | + .9 |
| | 5 | 2.252 | +1.2 |
| | 6 | 2.618 | -0.1 |
| 2 | 4 | 1.885 | +2.2 |
| | 5 | 2.252 | +1.8 |
| | 6 | 2.618 | +1.2 |
| 3 | 4 | 1.885 | +0.7 |
| | 5 | 2.252 | +2.2 |
| | 6 | 2.618 | -0.7 |
| 4 | 4 | 1.885 | +2.3 |
| | 5 | 2.252 | +0.8 |
| | 6 | 2.618 | -0.2 |
| 7 | 4 | 1.885 | +3.1 |
| | 5 | 2.252 | +1.4 |
| | 6 | 2.618 | -0.4 |
| 10 | 4 | 1.885 | +1.4 |
| | 5 | 2.252 | +2.6 |
| | 6 | 2.618 | +1.1 |
| 11 | 4 | 1.885 | +0.0 |
| | 5 | 2.252 | +1.9 |
| | 6 | 2.618 | -0.6 |

NOTE:

Design limits are ±0.003 inches from nominal.
Platform number clockwise from airfoil facing leading edge has the same number as the airfoil.

TABLE 48
CONTOURS AFTER BENCHING AND AFM OF PLATFORMS MILLED WITH DEVELOPMENT MACHINE ON STAGE 4 BLISK FOR ENGINE TESTING

| Platform Number | Location Number | Distance From TE Face (in) | Platform Contour Deviation from the Nominal Radius (mils) |
|---|---|---|---|
| 1 | 1 | .498 | -0.1 |
| | 2 | 1.021 | +2.3 |
| | 3 | 1.151 | +1.2 |
| 2 | 1 | .498 | +0.4 |
| | 2 | 1.021 | +3.0 |
| | 3 | 1.151 | +1.7 |
| 3 | 1 | .498 | +0.1 |
| | 2 | 1.021 | +3.2 |
| | 3 | 1.151 | +2.0 |
| 4 | 1 | .498 | -0.1 |
| | 2 | 1.021 | +3.2 |
| | 3 | 1.151 | +1.9 |
| 7 | 1 | .498 | -1.5 |
| | 2 | 1.021 | +1.7 |
| | 3 | 1.151 | +0.5 |
| 10 | 1 | .498 | +1.1 |
| | 2 | 1.021 | +3.7 |
| | 3 | 1.151 | +7.2 |
| 11 | 1 | .498 | -1.4 |
| | 2 | 1.021 | +2.1 |
| | 3 | 1.151 | +0.7 |

**NOTE:**

Design limits are ±.003 inches from nominal.
Platform number clockwise from airfoil facing leading edge has the same number as the airfoil.

LEGEND

Uncut Metal
Milled Pocket
Cerro Filled

NC PROGRAM TIME (MIN)

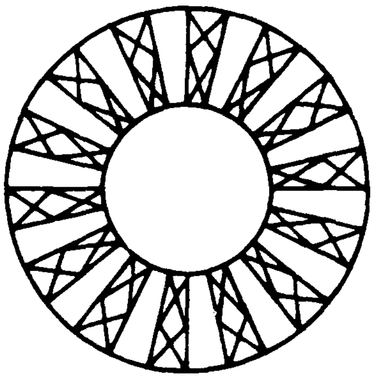
| | |
|---|---|
| Airfoil Rough | 21 |
| Airfoil Finish | 44 |
| Platform Finish | 40 |

NUMBER OF CUTTERS USED

| | |
|---|---|
| Airfoil Rough | 8 |
| Airfoil Finish | 3 |
| Platform Finish | 3 |

STEP 1

Cut 14 pockets total; roughed 14 pockets, then finished 14 pockets with airfoil finish cutter, then finished 14 platforms with platform finish cutter, filled all pockets with Cerro matrix.



STEP 2

Cut 14 pockets total; roughed 14 pockets, then finished 14 pockets with airfoil finish cutter, then finished 14 platforms with platform finish cutter.

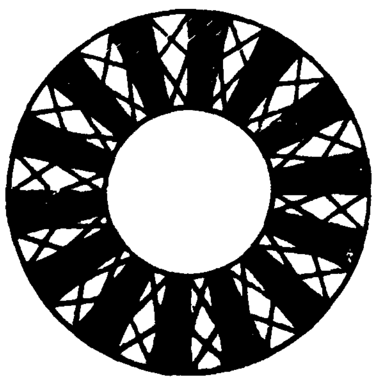


Figure 137. Procedure for Milling Airfoils and Platforms with Development Machine on Stage 3 Blisk for Engine Testing.

LEGEND

| | |
|---|---|
| Uncut Metal | |
| Milled Pocket | |
| Cerro Filled | |

NC PROGRAM TIME (MIN)

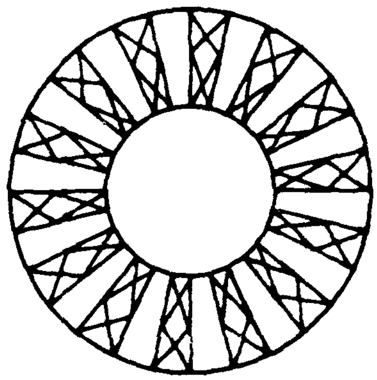
| | |
|---|---|
| Airfoil Rough | 16 |
| Airfoil Finish | 35 |
| Platform Finish | 37 |

NUMBER OF CUTTERS USED

| | |
|---|---|
| Airfoil Rough | 7 |
| Airfoil Finish | 9 |
| Platform Finish | 6 |

STEP 1

Cut 14 pockets total; roughed 14 pockets, then finished 14 pockets with airfoil finish cutter, then finished 14 platforms with platform finish cutter, filled all pockets with Cerro matrix.



STEP 2

Cut 14 pockets total; roughed 14 pockets, then finished 14 pockets with airfoil finish cutter, then finished 14 platforms with platform finish cutter.

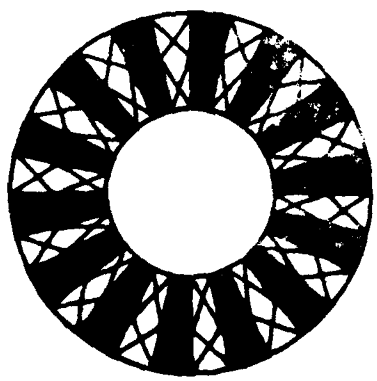


Figure 138. Procedure for Milling Airfoils and Platforms with Development Machine on Stage 4 Blisk for Engine Testing.

T700 BLISK DEVELOPMENT INSPECTION - AIRFOIL SURFACE ROUGHNESS REPORT Page 1 of 3

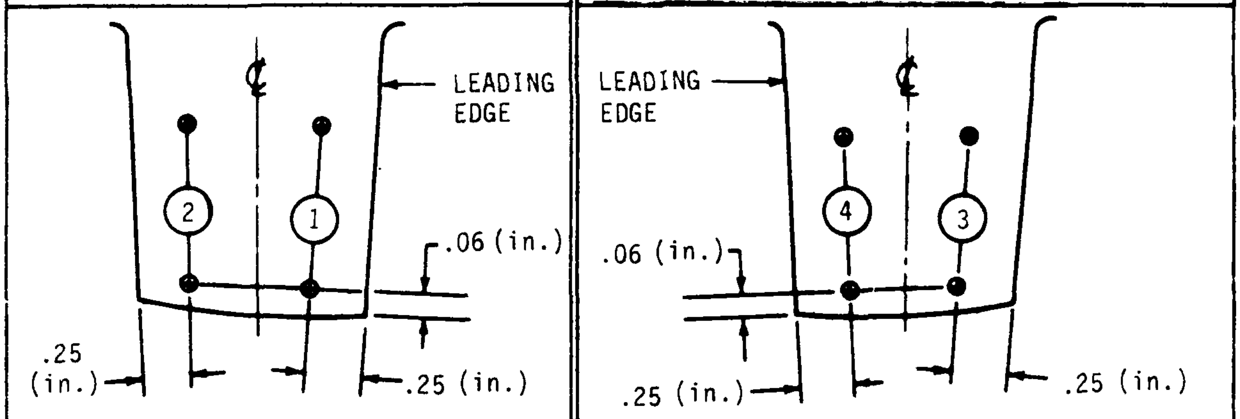
STAGE: 3 SERIAL NO. 15184
AFTER AFM
CAL 2 c 44

INSP BY: W. W. G.
DATE: 5-5-78

SET UP AND INSPECT PER W1 #RJL-72977 USING-BENDIX MICROCORDER

CONVEX SIDE: (Trace in Approx Location Shown)

CONCAVE SIDE: (Trace in Approx Location Shown)




| Blade No. | Sta. No. | Table Tilt Angle (Deg) | Length of Stroke (in.) | Record Ra (Average) ($\mu$ in. AA) | Sta. No. | Table Tilt Angle (Deg) | Length of Stroke (in.) | Record Ra (Average) ($\mu$ in. AA) | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 42 | 5/16 | 21 | 3 | 44 | 5/16 | 30 | |
| | 2 | 50 | 5/16 | 24 | 4 | 44 | 5/16 | 22 | |
| | 1 | | | 21 | 3 | | | 24 | |
| | 2 | | | 22 | 4 | | | 21 | |
| | 1 | | | 18 | 3 | | | 24 | |
| | | | | 15 | 4 | | | 28 | |

...Roughness After AFM of Airfoil Milled With Development ... Stage 3 Blisk for Engine Testing.

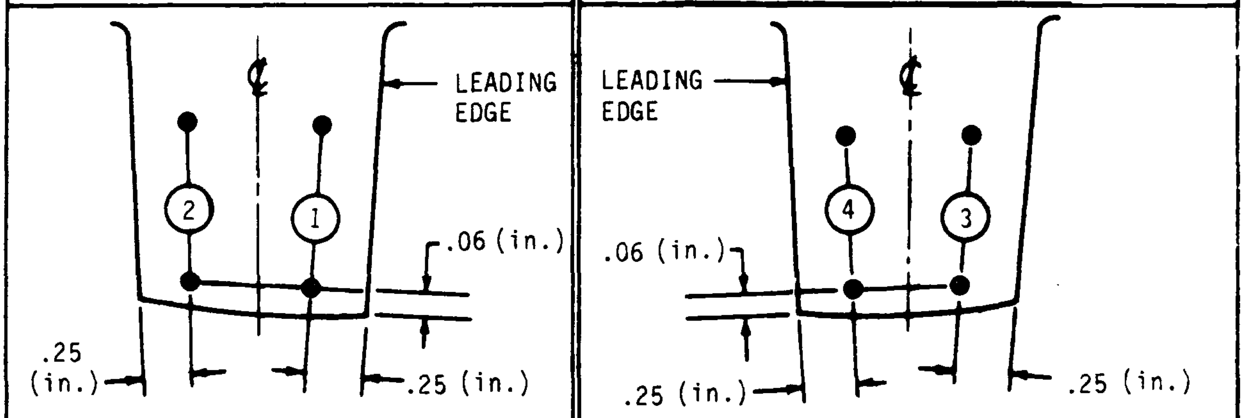
T700 BLISK DEVELOPMENT INSPECTION - AIRFOIL SURFACE ROUGHNESS REPORT Page 1 of 3

STAGE: 4    SERIAL NO. 15124 AFTER AFM CAL 20AA    INSP BY: W. W. G.

DATE: 5-5-78

SET UP AND INSPECT PER W1 #RJL-72977 USING-BENDIX MICROCORDER

CONVEX SIDE: (Trace in Approx Location Shown)    CONCAVE SIDE: (Trace in Approx Location Shown)




| Blade No. | Sta. No. | Table Tilt Angle (Deg) | Length of Stroke (in.) | Record Ra (Average) ($\mu$ in. AA) | Sta. No. | Table Tilt Angle (Deg) | Length of Stroke (in.) | Record Ra (Average) ($\mu$ in. AA) | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| 2 | 1 | 42 | 5/16 | 20 | 3 | 44 | 5/16 | 22 | |
| | | | | | | | | | |
| | 2 | 50 | 5/16 | 12 | 4 | 44 | 5/16 | 31 | |
| | | | | | | | | | |
| 4 | 1 | | | 19 | 3 | | | 26 | |
| | | | | | | | | | |
| | 2 | | | 17 | 4 | | | 15 | |
| | | | | | | | | | |
| 19 | 1 | | | 26 | 3 | | | 26 | |
| | | | | | | | | | |
| | 2 | | | 22 | 4 | | | 30 | |
| | | | | | | | | | |

Figure 140. Surface Roughness After AFM of Airfoils Milled With Development Machine on Stage 4 Blisk for Engine Testing.

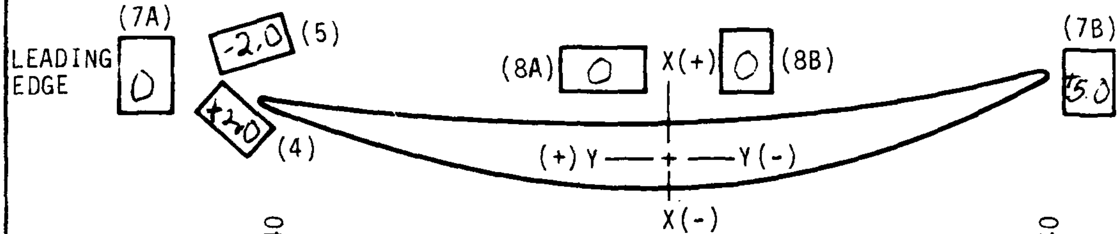
| | | |
|---|---|---|
| PART NO. | SER. NO. 15184 | STAGE 3 |
| OBSERVER: W W B | DATE: 5-8-78 | CHORD (DWG) |

AF NO. 1

SECT. H


| SECT | DIM |
|---|---|
| H | .8695 |

| | .040 | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | | | .040 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (3) THICKNESS | +2.4 | | +1.3 | | +2.3 | | +1.9 | | +2.1 | | +3.1 | | | | | | +3.1 | 2.2 | AVERAGE |
| CONCAVE (1) | 0 | | 0 | | 0 | | +.2 | | +.2 | | | | | | | | +.2 | .2 | CONTOUR SPREAD |




| | .040 | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | .040 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CONVEX (2) | 0 | | -.6 | | -.9 | | -1.3 | | -1.0 | | -.7 | | | | | | 0 | | CONTOUR (SPREAD) |

COMMENTS ALL VALUES ARE DEVIATION FROM NOMINAL AND ARE RECORDED x 1000 i.e. .2 = .0002 in.

SET UP AND INSPECT PER

| TRACE DATA - RECORD THE FOLLOWING | ROTARY TABLE POSITION (BLADE CENTRAL) |
|---|---|
| | DRAWING: ACTUAL: |

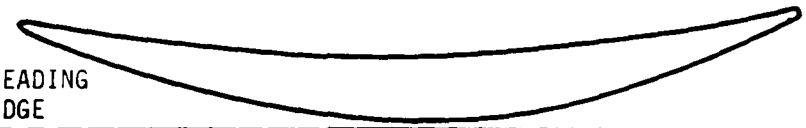
RECORD ALL DATA FROM COMPARATOR MEASUREMENTS AS FOLLOWS:

| DRAWING LIMITS | ITEM NO. | DESCRIPTION (ALL NUMBERS ARE INCHES EXCEPT AS NOTED) |
|---|---|---|
| ±.0015 | (1) | Contour Deviation - Concave Side |
| ±.0015 | (2) | Contour Deviation - Convex Side |
| +.004 -.003 | (3) | Thickness - Deviation from Nominal (+ or -) |
| ±.008 | (4) | Tip Location - Deviation from Nominal - Convex Side |
| ±.005 B-B) | (5) | Tip Location - Deviation from Nominal - Concave Side |
| +.007/-.009 | (6) | Chord - Full (Deviation from Nominal)(By Indicator) = +1.5 |
| N/A | (7A) | Chord from Center to Leading Edge |
| N/A | (7B) | Chord from Center to Trailing Edge |
| ±.002 ±.005 master central | (8A) | Y-Stacking Axis Shift (+ ←→ -) |
| ±.002 master | (8B) | X-Stacking Axis Shift (↑ +) (↓ -) |
| ±.0°45' | (9) | Warp Angle - Record at Best Fit: 0°0' |
| ±.005 | (10) | Blade - Circumference True Position (At Master Section Only) (Deviation from Nominal) |

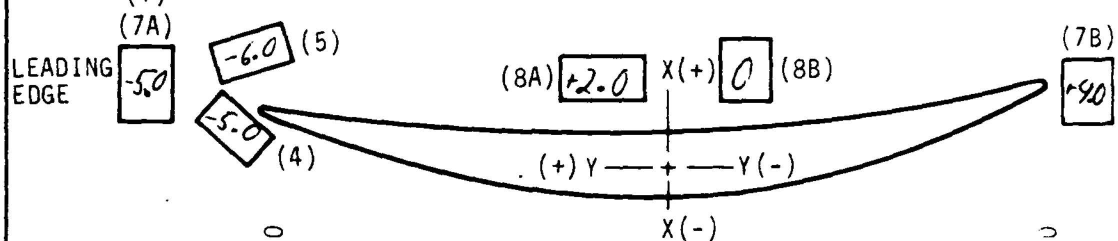
Figure 141. Geometry After AFM of Typical Airfoil Milled With Development Machine on Stage 3 Blisk for Engine Testing.

| | | |
|---|---|---|
| PART NO. | SER. NO. 15184 | STAGE 4 |
| OBSERVER: w w R | DATE: 5-9-78 | CHORD (DWG) |
| AF NO. 11 | | SECT / DIM |
| SECT. V | | V / .8095 |
| AFT AFM | | |

LEADING EDGE



| | .040 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | .040 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (3) THICKNESS | +1.6 | +1.3 | +1.5 | +2.3 | +2.7 | +2.4 | | | +3.3 | 2.2 | AVERAGE |
| CONCAVE (1) | 0 | -.2 | -.2 | -.3 | 0 | 0 | | | 0 | .3 | CONTOUR SPREAD |




| | .040 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | .040 | |
|---|---|---|---|---|---|---|---|---|---|---|
| CONVEX (2) | 0 | 0 | 0 | -.1 | -.1 | -.1 | | | +.1 | CONTOUR (SPREAD) |

COMMENTS ALL VALUES ARE DEVIATION FROM NOMINAL AND ARE RECORDED X 1000 i.e. 2.2 = .0022 IN

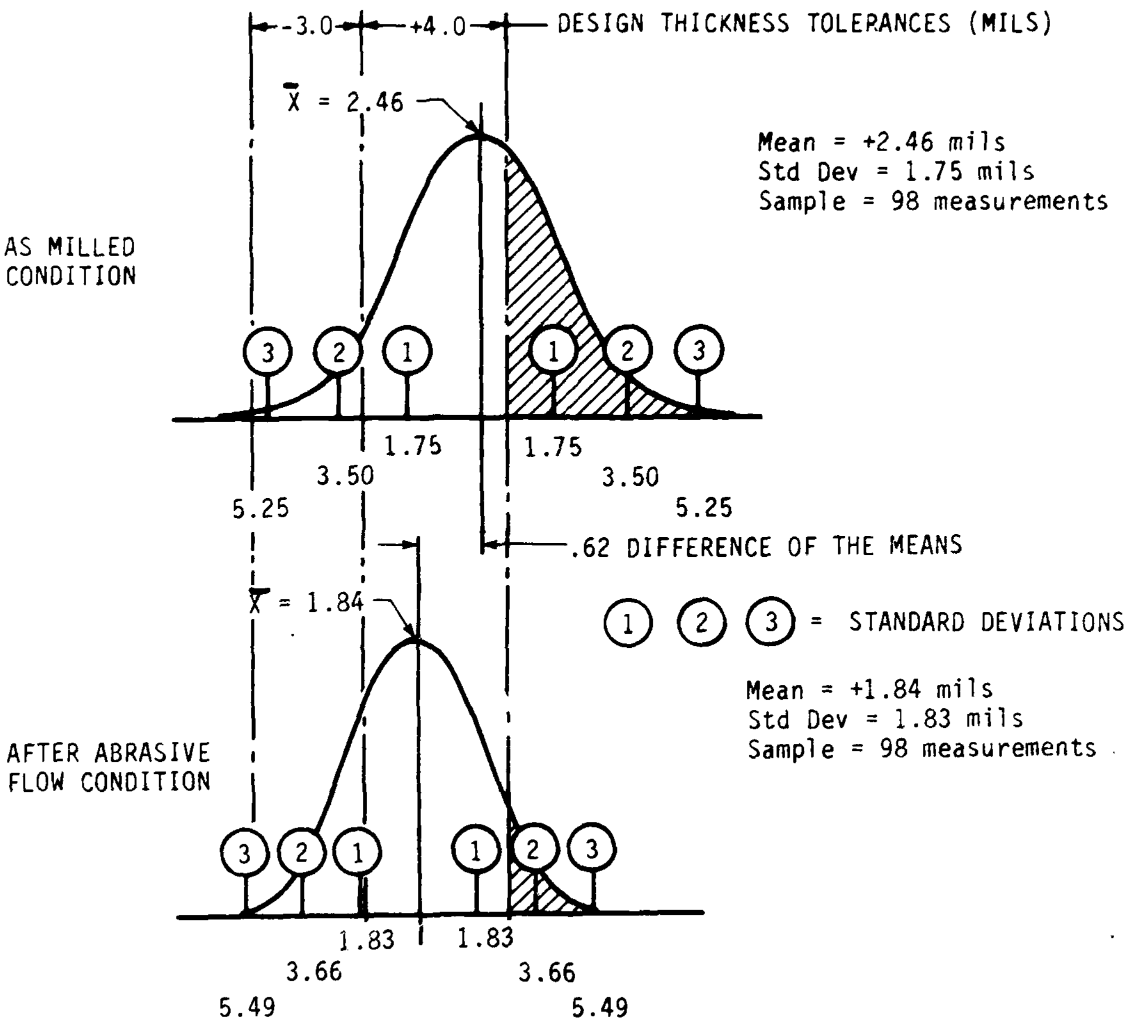
SET UP AND INSPECT PER

| TRACE DATA - RECORD THE FOLLOWING | ROTARY TABLE POSITION (BLADE CENT AL) |
|---|---|
| | DRAWING: ACTUAL: |

RECORD ALL DATA FROM COMPARATOR MEASUREMENTS AS FOLLOWS:

| DRAWING LIMITS | ITEM NO. | DESCRIPTION (ALL NUMBERS ARE INCHES EXCEPT AS NOTED) |
|---|---|---|
| ±.0015 | (1) | Contour Deviation - Concave Side |
| ±.0015 | (2) | Contour Deviation - Convex Side |
| +.004 -.003 | (3) | Thickness - Deviation from Nominal (+ or -) |
| ±.008 | (4) | Tip Location - Deviation from Nominal - Convex Side |
| ±.005 B-B) | (5) | Tip Location - Deviation from Nominal - Concave Side |
| +.007/-.009 | (6) | Chord - Full (Deviation from Nominal)(By Indicator) = -3.5 |
| N/A | (7A) | Chord from Center to Leading Edge |
| N/A | (7B) | Chord from Center to Trailing Edge |
| ±.002 ±.005 master central | (8A) | Y-Stacking Axis Shift (+ ←→ -) |
| ±.002 master | (8B) | X-Stacking Axis Shift (↑ +) (↓ -) |
| ±.0°45' | (9) | Warp Angle - Record at Best Fit: 0°0' |
| ±.005 | (10) | Blade - Circumference True Position (At Master Section Only) (Deviation from Nominal) |

Figure 142. Geometry After AFM of Typical Airfoil Milled With Development Machine on Stage 4 Blisk for Engine Testing.



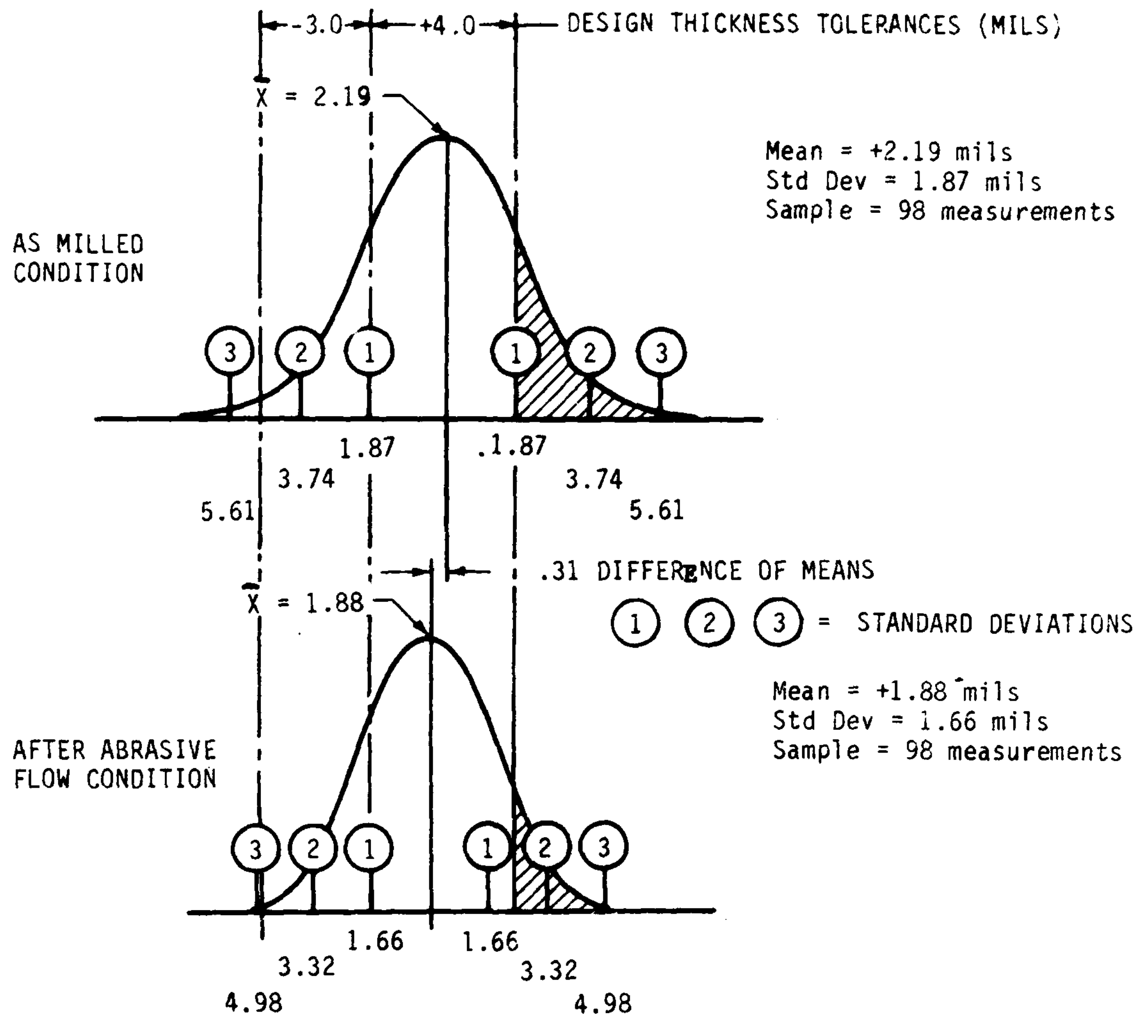

Statistical Definitions:

95.4% of the airfoil thickness measurements are within ±2 standard deviation and 99.7% are within ±3 standard deviation.

Blisk:

Stage 3, Serial No. 15184, Sections E and H

Figure 143. Statistical Analysis of Thickness Measurements of Two Upper Sections of Airfoils Milled With Development Machine on Stage 3 Blisk for Engine Testing.



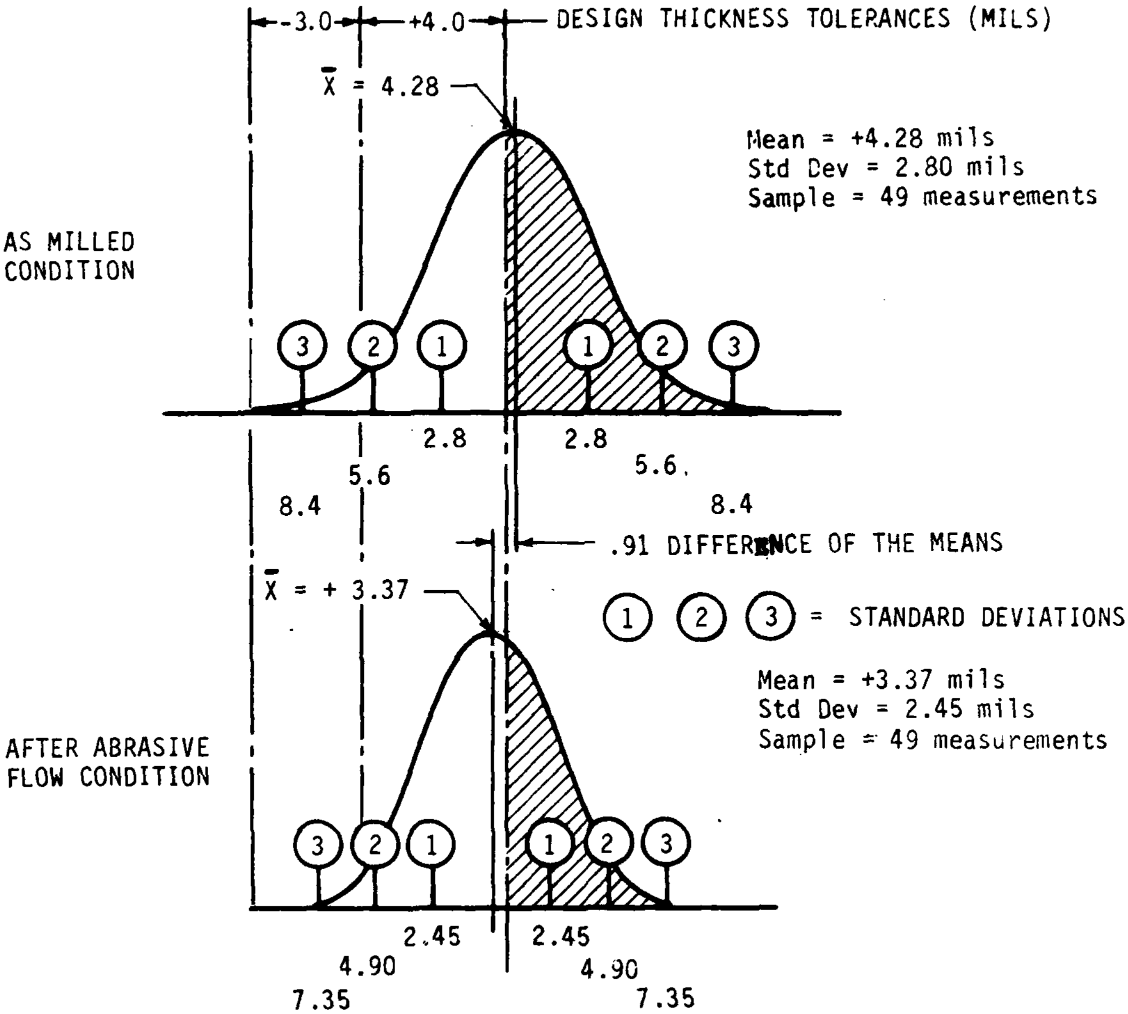

Statistical Definitions:

95.4% of the airfoil thickness measurements are within ±2 standard deviation and 99.7% are within ±3 standard deviation.

Blisk:

Stage 4, Serial No. 15184, Sections R and V

Figure 144. Statistical Analysis of Thickness Measurements of Two Upper Sections of Airfoils Milled With Development Machine on Stage 4 Blisk for Engine Testing.



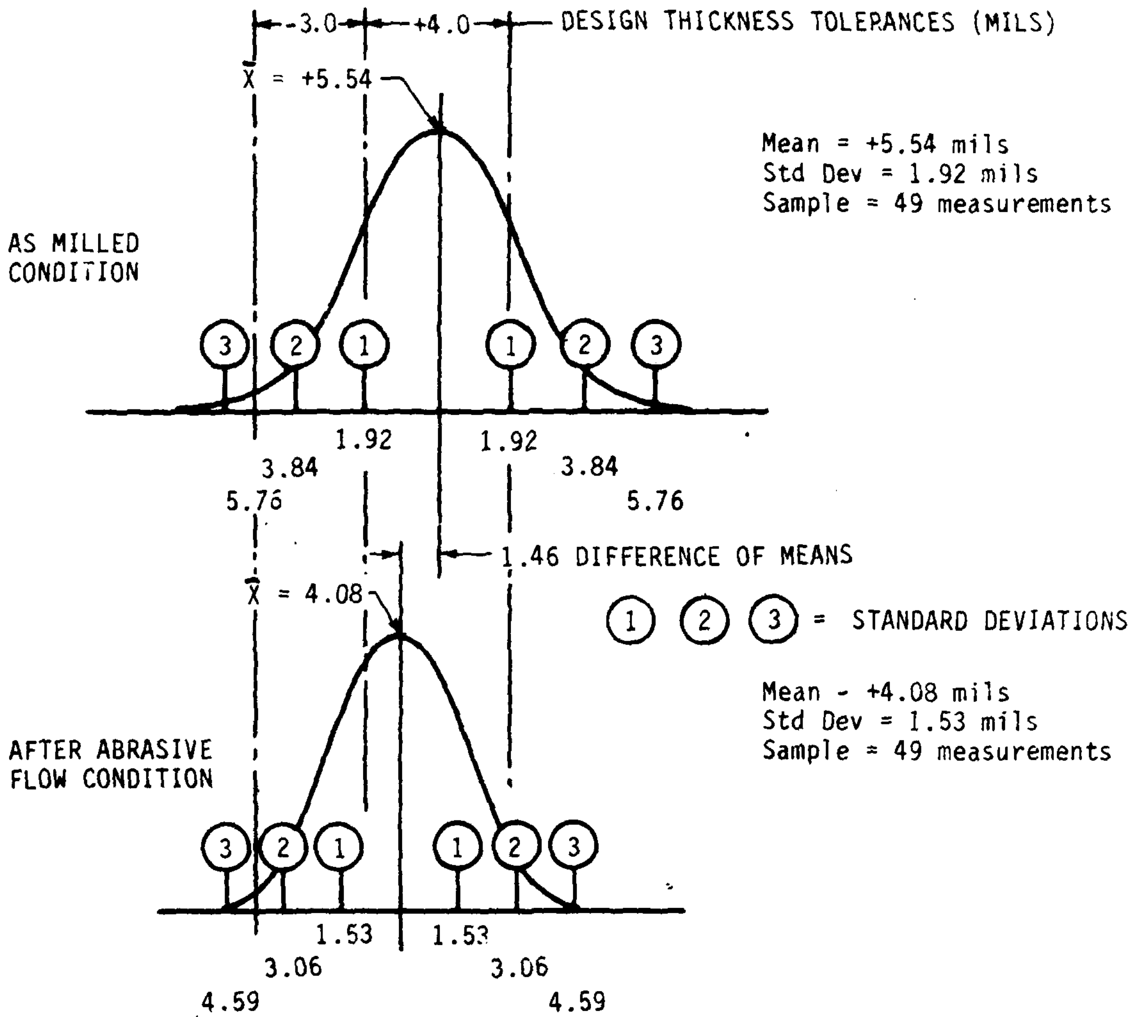

Statistical Definitions:

95.4% of the airfoil thickness measurements are within ±2 standard deviation and 99.7% are within ±3 standard deviation.

Blisk:

Stage 3, Serial No. 15184, Section C

Figure 145. Statistical Analysis of Thickness Measurements of Lower Section of Airfoils Milled With Development Machine on Stage 3 Blisk for Engine Testing.




Statistical Definitions:

95.4% of the airfoil thickness measurements are within ±2 standard deviation and 99.7% are within ±3 standard deviation.

Blisk:

Stage 4, Serial No. 15184, Section N

Figure 146. Statistical Analysis of Thickness Measurements of Lower Section of Airfoils Milled With Development Machine on Stage 4 Blisk for Engine Testing.

PROCESS CAPABILITY

STAGE 5 BLISK

STAGE 5 BLISK PROCESS CAPABILITY

All airfoils and platforms were machined with the development machine and the production AFM machine and fixture on the first complete Stage 5 blisk to be produced during the course of this development program. This blisk was produced for engine testing.

Platforms and the blend surfaces on airfoils adjacent to platforms were benched to reduce roughness prior to surface finishing by abrasive flow machining. No difficulty was experienced with benching.

No difficulties were experienced with milling or AFM finishing.

Milling parameters for Stage 5 blisk airfoils and platforms are shown in Table 49 (pg 272). Abrasive flow machinery parameters are given in Table 50 (pg 273). The milling sequence was the same as used for the Stage 2 blisk, as shown in Figure 134( pg 250). Typical results of measurements of milled airfoil geometry, are given in Tables 51-52 (pgs 274-275) and Figures 147-148 (pgs 277-278). Results of platform contour measurements are given in Table 53 (pg 276) and typical airfoil surface roughness results in Figure 149 (pg 279).

The roughness of airfoil surfaces, milled with the airfoil finish contour milling cutter, ranged from about 80 to 140 microninches AA. Compared to roughly 70 microinches AA for other stages. The milled surface appearance varied from showing clearly defined cutting path lines, as with other stages to a mottled appearance not previously encountered. As a consequence, a relatively large amount of abrasive flow machining and benching were required to obtain finished airfoil surface roughness of 32 microinches AA.

Increase in Cutter Diameter for Stage 5 Blisk Milling

Stage 5 blisk airfoils were milled on a blisk blank using new NC programs and 1/4 inch diameter rough and finish milling cutters, to evaluate the capability of these cutters to produce design geometry, and improve finish surface roughness over that produced on the first engine part milled with 3/16 inch diameter cutters. The results were excellent and indicated that production milling should be performed with 1/4 inch diameter cutters.

TABLE 49
CUTTING PARAMETERS FOR STAGE 5 BLISK
AIRFOILS AND PLATFORMS MILLED WITH DEVELOPMENT MACHINE

| Operation | Cutting Speed (sft/min) | Lineal Feed (inch/min) | Downfeed (inch/pass) | Depth of Cut (inch) | Cutter Extension (inch) | Cutter Geometry No. Flutes (degree) | Cutter Geometry Helix Angle (degree) | Cutter Geometry Rake Angle (degree) | Cutter Geometry Relief Angle (degree) |
|---|---|---|---|---|---|---|---|---|---|
| Airfoil Rough Contour Milling | 184 | 6 | .060 | .187 Step Cut | 1.0 | 4 | 30 | 0 | 6 |
| Airfoil Finish Contour Milling | 147 | 18 | .010 | .020 | 1.0 | 12 | 30 | 30 neg | 45 |
| Platform Finish Contour Milling | 367 | 18 | .010 | .010 | 1.2 | 12 | 30 | 30 neg | 45 |

**NOTES:**

Blank Material - AM355
Blank Hardness - 34-36 RC
Cutter Material - Carbide Grade 883

TABLE 50

AFM PARAMETERS USED TO FINISH STAGE 5 BLISK AIRFOILS AND PLATFORMS MILLED ON DEVELOPMENT MACHINE FOR ENGINE TESTING

**AFM PARAMETERS**

| | | |
|---|---|---|
| Part | - | Stage 5 AM355 Blisk SN 80125 |
| Machine | - | Dynetics Production - HL60CF-830 |
| Tooling | - | Production Tooling |
| Media | - | D080-20A (61) -36A (73) -700(40) |
| Media Temperature | | 99°F Avg |
| Media Pressure | - | 150 psi |
| Total Cycles | - | 92 |
| Total Time | - | 133 minutes |

**PROCEDURE:**

This blisk was abrasive flowed in two operations. First operation was for 32 cycles and after chord and surface finish checks were made, a second operation of 20 cycles was applied. A second check of surface finish and chord indicated that ample chord was available and surface finish required improvement. Modifications were made to the flow director and a third operation of 40 cycles was applied.

TABLE 51
GEOMETRY OF AIRFOILS AS MILLED WITH DEVELOPMENT MACHINE ON STAGE 5 BLISK FOR ENGINE TESTING

| Airfoil Number | Section | Contour Deviation Spread (mils) | | Thickness Deviation (mils) | | | Chord Deviation (mils) |
|---|---|---|---|---|---|---|---|
| | | Concave | Convex | Max | Min | Avg | |
| 5 | C | 0.9 | 0.5 | + 3.6 | +2.0 | +2.6 | +13.0 |
| | E | 1.2 | 1.2 | + 4.3 | +2.3 | +3.0 | +11.5 |
| | G | 1.0 | 1.0 | + 4.6 | +2.8 | +3.7 | +15.0 |
| 7 | C | 0.7 | 0.6 | + 2.0 | 0 | +0.8 | +11.0 |
| | E | 1.0 | 1.4 | + 2.8 | +0.6 | +1.5 | +10.5 |
| | G | 0.9 | 1.0 | + 4.1 | +1.9 | +2.6 | +11.5 |
| 13 | C | 0.2 | 0.6 | + 2.8 | +0.6 | +1.8 | +12.0 |
| | E | 0.9 | 0.6 | + 3.9 | +1.7 | +2.5 | +12.5 |
| | G | 1.0 | 0.3 | + 3.5 | +2.3 | +2.9 | +11.5 |
| 14 | C | 0.9 | 1.1 | + 3.7 | +1.8 | +2.5 | +14.0 |
| | E | 1.6 | 0.8 | + 4.1 | +1.8 | +2.7 | +10.5 |
| | G | 0.3 | 0.6 | + 4.2 | +2.0 | +3.0 | +12.5 |
| 19 | C | 0.7 | 0.7 | + 3.6 | +2.8 | +3.0 | +12.0 |
| | E | 0.9 | 0.7 | + 4.6 | +1.9 | +3.5 | +12.5 |
| | G | 0.6 | 0.4 | + 5.3 | +4.3 | +4.9 | +13.5 |
| 21 | C | 0.4 | 1.4 | + 2.0 | +0.3 | +1.2 | +11.0 |
| | E | 0.9 | 0.3 | + 3.3 | +0.9 | +2.0 | +09.5 |
| | G | 1.2 | 0 | + 3.5 | +4.3 | +2.3 | +10.5 |
| 28 | C | 0.2 | 0.9 | + 3.1 | 0 | +1.3 | +13.0 |
| | E | 0.9 | 0.9 | + 4.3 | +2.9 | +3.5 | +12.5 |
| | G | 0.5 | 0.9 | + 4.0 | +3.1 | +3.4 | +12.5 |
| 30 | C | 1.0 | 1.3 | + 0.8 | -2.9 | -1.0 | +13.0 |
| | E | 1.2 | 0.2 | + 0.9 | 0 | +0.1 | +06.5 |
| | G | 0.9 | 0.6 | + 1.0 | -0.2 | +0.4 | +07.5 |

TABLE 52
GEOMETRY AFTER AFM OF AIRFOILS MILLED WITH
DEVELOPMENT MACHINE ON STAGE 5 BLISK FOR ENGINE TESTING

| Airfoil Number | Section | Contour Deviation Spread (mils) Concave | Convex | Thickness Deviation (mils) Max | Min | Avg | Chord Deviation (mils) |
|---|---|---|---|---|---|---|---|
| 5 | C | 0.3 | 0.5 | +3.3 | -0.4 | +1.2 | -06.0 |
| | E | 0.7 | 0.6 | +3.3 | +0.1 | +1.4 | -03.0 |
| | G | 0.3 | 0.2 | +3.8 | +1.5 | +2.3 | -02.0 |
| 7 | C | 0.6 | 0.2 | +1.0 | -1.7 | -0.4 | -10.0 |
| | E | 0.6 | 0.6 | +1.8 | -1.2 | 0 | -08.5 |
| | G | 0.2 | 0.8 | +3.0 | +0.8 | +1.4 | +05.0 |
| 13 | C | 0.2 | 1.0 | +1.8 | -1.0 | +0.3 | -09.0 |
| | E | 0.5 | 0 | +2.3 | 0 | +0.8 | -07.5 |
| | G | 0.4 | 0 | +2.5 | +0.2 | +1.2 | -03.5 |
| 14 | C | 0.3 | 0.9 | +2.7 | +0.6 | +0.7 | -06.5 |
| | E | 0.3 | 0.4 | +2.4 | +0.1 | +0.8 | -06.5 |
| | G | 0.9 | 0.7 | +2.4 | +0.6 | +1.3 | -04.0 |
| 19 | C | 0.5 | 0.8 | +2.8 | +0.7 | +1.6 | +02.5 |
| | E | 0.9 | 1.2 | +2.9 | +1.4 | +2.2 | -05.0 |
| | G | 0.4 | 0.4 | +4.7 | +3.0 | +3.6 | -02.0 |
| 21 | C | 0 | 0.7 | +2.3 | -0.3 | +0.2 | +07.0 |
| | E | 0.4 | 0.9 | +2.3 | +0.6 | +1.1 | +08.5 |
| | G | 0.6 | 0.4 | +2.0 | 0 | +0.5 | +06.5 |
| 28 | C | 0.8 | 1.0 | +2.1 | -1.0 | +0.1 | -08.0 |
| | E | 0.2 | 0.6 | +2.8 | +1.0 | +1.7 | -03.5 |
| | G | 0 | 0.5 | +2.5 | +1.9 | +2.3 | -03.5 |
| 30 | C | 0.3 | 0.8 | +0.9 | -3.3 | -2.0 | -16.0 |
| | E | 0.8 | 0.6 | +0.7 | -2.0 | -1.3 | -14.5 |
| | G | 0.2 | 0.5 | +0.6 | -1.2 | -0.7 | -16.5 |

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T700 BLISK AND IMPELLER MANUFACTURING PROCESS DEVELOPMENT PROGR--ETC(U)
NOV 79 W A HUNTER, G A GRIMMER    DAAJ01-75-C-0844
UNCLASSIFIED    R80AEG035    USAAVRADCOM-TR-80-F-1    NL



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TABLE 53

CONTOURS AFTER BENCHING AND AFM OF PLATFORMS MILLED WITH DEVELOPMENT MACHINE ON STAGE 5 BLISK FOR ENGINE TESTING

| Platform Number | Location Number | Distance From TE Face (in) | Platform Contour Deviation from the Nominal Radius (mils) |
|---|---|---|---|
| 16 | 1 | 1.532 | +1.5 |
| | 2 | 1.386 | +0.9 |
| | 3 | 0.979 | +1.3 |
| | 4 | 0.920 | +0.9 |
| 20 | 1 | 1.532 | +1.1 |
| | 2 | 1.386 | +0.8 |
| | 3 | 0.979 | +0.8 |
| | 4 | 0.920 | +0.5 |
| 21 | 1 | 1.532 | +1.5 |
| | 2 | 1.386 | 0.0 |
| | 3 | 0.979 | +0.5 |
| | 4 | 0.920 | +0.3 |
| 22 | 1 | 1.532 | +1.3 |
| | 2 | 1.386 | +0.2 |
| | 3 | 0.979 | +0.3 |
| | 4 | 0.920 | +0.1 |
| 23 | 1 | 1.532 | +1.4 |
| | 2 | 1.386 | +0.1 |
| | 3 | 0.979 | +0.4 |
| | 4 | 0.920 | +0.3 |
| 24 | 1 | 1.532 | +1.7 |
| | 2 | 1.386 | +0.4 |
| | 3 | 0.979 | +0.4 |
| | 4 | 0.920 | +0.5 |
| 25 | 1 | 1.532 | +2.6 |
| | 2 | 1.386 | +1.2 |
| | 3 | 0.979 | +1.6 |
| | 4 | 0.920 | +1.3 |
| 31 | 1 | 1.532 | +1.9 |
| | 2 | 1.386 | +0.6 |
| | 3 | 0.979 | +1.1 |
| | 4 | 0.920 | +1.1 |

| | | |
|---|---|---|
| PART NO. 6038T09 | SER. NO. 80125 | STAGE 5 |
| OBSERVER: | DATE: 3-9-78 | CHORD (DWG) |

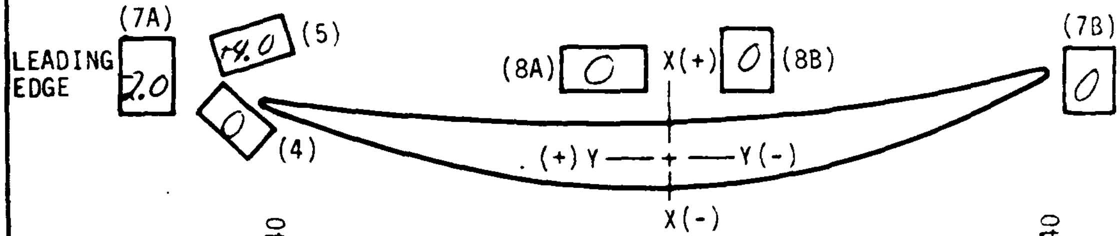
AF NO. 5

SECT. 6-6

AFTER AFM

| SECT | DIM |
|---|---|
| 6-6 | .6565 |


| | .040 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | .040 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (3) THICKNESS | +1.5 | +1.5 | +1.5 | +2.2 | +2.5 | +3.1 | | | +3.8 | +2.3 | AVERAGE |
| CONCAVE (1) | 0 | -.3 | -.3 | -.3 | -.3 | -.3 | | | 0 | .3 | CONTOUR SPREAD |




| | .040 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | .040 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CONVEX (2) | 0 | 0 | 0 | -.2 | -.2 | -.2 | | | -.1 | .2 | CONTOUR (SPREAD) |

COMMENTS ALL VALUES ARE DEVIATION FROM NOMINAL AND ARE RECORDED X 1000 i.e. 7.2 = .0072

SET UP AND INSPECT PER

| TRACE DATA - RECORD THE FOLLOWING | ROTARY TABLE POSITION (BLADE CENTRAL) |
|---|---|
| | DRAWING: ACTUAL: |

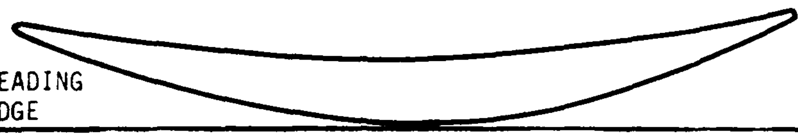
RECORD ALL DATA FROM COMPARATOR MEASUREMENTS AS FOLLOWS:

| DRAWING LIMITS | ITEM NO. | DESCRIPTION (ALL NUMBERS ARE INCHES EXCEPT AS NOTED) |
|---|---|---|
| ±.0015 | (1) | Contour Deviation - Concave Side |
| ±.0015 | (2) | Contour Deviation - Convex Side |
| +.004 -.003 | (3) | Thickness - Deviation from Nominal (+ or -) |
| ±.008 | (4) | Tip Location - Deviation from Nominal - Convex Side |
| ±.005 B-B) | (5) | Tip Location - Deviation from Nominal - Concave Side |
| +.007/-.009 | (6) | Chord - Full (Deviation from Nominal)(By Indicator) = 2.0 |
| N/A | (7A) | Chord from Center to Leading Edge |
| N/A | (7B) | Chord from Center to Trailing Edge |
| ±.002±.005 master central | (8A) | Y-Stacking Axis Shift (+◄►-) |
| ±.002 master | (8B) | X-Stacking Axis Shift (↑ +) (↓ -) |
| ±.0°45' | (9) | Warp Angle - Record at Best Fit: 0°0' |
| ±.005 | (10) | Blade - Circumference True Position (At Master Section Only) (Deviation from Nominal) |

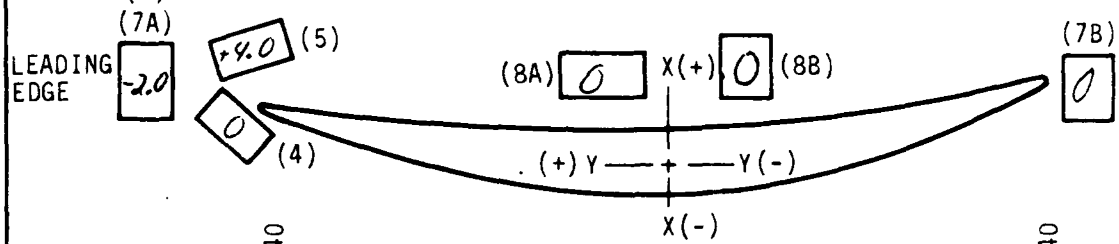
Figure 147. Geometry After AFM of Typical Airfoil Milled With Development Machine on Stage 5 Blisk for Engine Testing.

| PART NO. 6038 T09 | SER. NO. 80125 | STAGE 5 |
|---|---|---|
| OBSERVER: W W G | DATE: 3-9-78 | CHORD (DWG) |

| AF NO. 5 | | SECT | DIM |
|---|---|---|---|
| SECT. 6-6 | | 66 | .6565 |
| AFTER AFM | LEADING EDGE | | |



| | .040 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | .040 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (3) THICKNESS | +1.5 | +1.5 | +1.5 | +2.2 | +2.5 | +3.1 | | | +3.8 | +2.3 | AVERAGE |
| CONCAVE (1) | 0 | -.3 | -.3 | -.3 | -.3 | -.3 | | | 0 | .3 | CONTOUR SPREAD |




| | .040 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | .040 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CONVEX (2) | 0 | 0 | 0 | -.2 | -.2 | -.2 | | | -.1 | .2 | CONTOUR (SPREAD) |

COMMENTS ALL VALUES ARE DEVIATION FROM NOMINAL AND ARE RECORDED X 1000 i.e. 7.2 = .0072 in

SET UP AND INSPECT PER

| TRACE DATA - RECORD THE FOLLOWING | ROTARY TABLE POSITION (BLADE CENTRAL) |
|---|---|
| | DRAWING: ACTUAL: |

RECORD ALL DATA FROM COMPARATOR MEASUREMENTS AS FOLLOWS:

| DRAWING LIMITS | ITEM NO. | DESCRIPTION (ALL NUMBERS ARE INCHES EXCEPT AS NOTED) |
|---|---|---|
| ±.0015 | (1) | Contour Deviation - Concave Side |
| ±.0015 | (2) | Contour Deviation - Convex Side |
| +.004 -.003 | (3) | Thickness - Deviation from Nominal (+ or -) |
| ±.008 | (4) | Tip Location - Deviation from Nominal - Convex Side |
| ±.005 B-B) | (5) | Tip Location - Deviation from Nominal - Concave Side |
| +.007/-.009 | (6) | Chord - Full (Deviation from Nominal)(By Indicator) = -2.0 |
| N/A | (7A) | Chord from Center to Leading Edge |
| N/A | (7B) | Chord from Center to Trailing Edge |
| ±.002 ±.005 master central | (8A) | Y-Stacking Axis Shift (+◄►-) |
| ±.002 master | (8B) | X-Stacking Axis Shift (↑ +) (↓ -) |
| ±.0°45' | (9) | Warp Angle - Record at Best Fit: 0°0' |
| ±.005 | (10) | Blade - Circumference True Position (At Master Section Only) (Deviation from Nominal) |

Figure 148. Geometry After AFM of Typical Airfoil Milled With Development Machine on Stage 5 Blisk for Engine Testing.

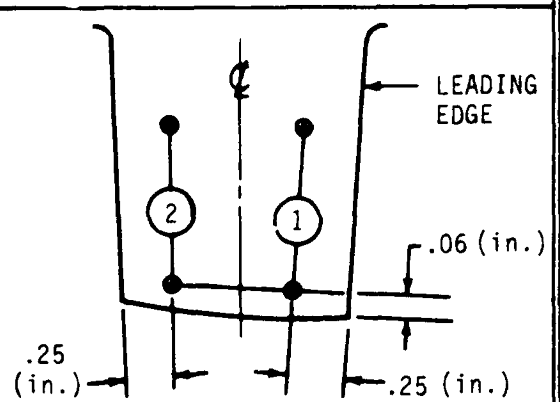
T700 BLISK DEVELOPMENT INSPECTION - AIRFOIL SURFACE ROUGHNESS REPORT

STAGE: 5 SERIAL NO. 80125 INSP BY: W.W.G.

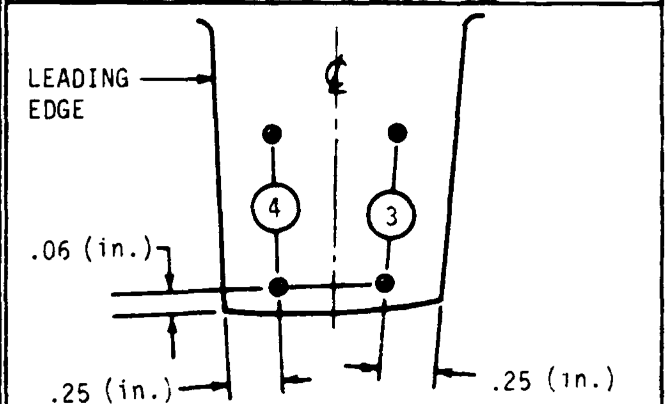
DATE: 3-9-78

SET UP AND INSPECT PER W1 #RJL-72977 USING-BENDIX MICROCORDER

CONVEX SIDE:
(Trace in Approx Location Shown)




CONCAVE SIDE:
(Trace in Approx Location Shown)




| Blade No. | Sta. No. | Table Tilt Angle (Deg) | Length of Stroke (in.) | Record Ra (Average) (μ in.AA) | Sta. No. | Table Tilt Angle (Deg) | Length of Stroke (in.) | Record Ra (Average) (μ in.AA) | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| 5 | 1 | 47 | 5/16 | 20 | 3 | 54 | 5/16 | 26 | |
| | 2 | 60 | 5/16 | 30 | 4 | 50 | 5/16 | 21 | |
| 7 | 1 | | | 22 | 3 | | | 31 | |
| | 2 | | | 19 | 4 | | | 18 | |
| 13 | 1 | | | 21 | 3 | | | 25 | |
| | 2 | | | 18 | 4 | | | 22 | |

Figure 149. Surface Roughness After AFM and Benching of Airfoils Milled With Development Machine on Stage 5 Blisk for Engine Testing.

PROCESS CAPABILITY

IMPELLER

## IMPELLER PROCESS CAPABILITY

Airfoils on the first impeller were milled on the production machine, and finished with the production AFM machine and fixture. This impeller was produced for engine testing. The milling sequence and parameters are given in Figure 150 (pg 292) and Table 54 (pg 282). Abrasive flow machining parameters are given in Table 55 (pg 283). Measurements of airfoils and hub flow paths showed that the contour milling process was capable of producing geometry which, for the most part, conformed to design limits. Typical measurement results, after benching and AFM, are shown in Tables 56-58 (pgs 284-288) and Figures 151 (pg 293).

### Statistical Analysis of Impeller Process Capability

A statistical analysis was performed on airfoil thickness and true position measurements taken from the first impeller, to obtain an evaluation of process capability with respect to these characteristics. The analysis was made on the basis of a normal distribution. Typical results are shown in Tables 59-60 (pgs 289-290).

The calculated standard deviation for airfoil thickness of 2.15 mils indicated that approximately 95% of thickness measurements for all airfoils will fall within a spread of 8.6 mils, which is between the design tolerance spreads of 6 and 12 mils. It was estimated that about 90 percent of thickness measurements should fall within the appropriate tolerance spread. However, to utilize this capability to maximum advantage, mean thickness would have to be at design nominal.

Mean thickness was calculated to be 6.97 mils above design nominal for all airfoils. Additional work was required to reduce this to a value much closer to nominal.

The airfoil true position standard deviation was calculated to be 2.92 mils. This indicated that approximately 90% of true position measurements for all airfoils will fall within the design tolerance spread of 10 mils.

### Improved Impeller Process Capability

HECTRAN programs were revised to produce airfoils with reduced thickness. Three impeller airfoils were milled on the development machine and three on the production machine using the new Carboloy* 820 cutters. The geometry of the milled airfoils was measured and analyzed.

A statistical analysis was conducted on the measured data and is presented in Table 61 (pg 291). The mean thickness for the three airfoils, milled with the production machine, was about two mils greater than for the three airfoils milled with the development machine. Mean thickness of all six airfoils was 1.7 mils above nominal, and was successfully reduced from that for the first impeller.

*General Electric Trademark

TABLE 54

CUTTING PARAMETERS USED FOR MILLING AIRFOILS AND HUBS WITH PRODUCTION MACHINE ON IMPELLER FOR ENGINE TESTING

| | | | | | | | | Cutter Geometry | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Operation | Cutting Speed (sft/min) | Lineal Feed (inch/min) | Down feed (inch/pass) | Depth of Cut (inch) | Cutter Exten-sion (inch) | Cutter Diam. (inch) | No. Flutes | Helix Angle (deg) | Rake Angle (deg) | Relief Angle (deg) | Corner Radius (Inch) |
| Airfoil Rough | 75 | 3.0-4.2 | .070 | .312 | 1.0 | .312 | 6 | 30 | 0 | 6 | .060 |
| Airfoil Rough | 74 | .6 | .070 | .187 | 1.0 | .187 | 4 | 30 | 0 | 6 | .060 |
| Hub Rough | 75 | 2.4 | Vari-able | .028 | 1.0 | .187 | 4 | 30 | 0 | 6 | .060 |
| LE Finish | 98 | 4.5 | Plunge | .006 | 1.1 | .312 | 24 | 30 | -30 | 30 | .156 |
| Airfoil Finish | 99 | 9.0 | .035 | .015 | 1.0 | .187 | 12 | 30 | -30 | 30 | .093 |
| Hub Finish | 130 | 7.5 | .015 | .018 | 1.0 | .187 | 12 | 30 | -30 | 30 | .093 |
| Fillet Finish | 67 | 9.0 | .035 | .010 | 1.15 | .125 | 12 | 30 | -30 | 30 | .062 |

TABLE 55
AFM PARAMETERS USED TO FINISH AIRFOILS AND
HUB SURFACE MILLED WITH PRODUCTION MACHINE ON IMPELLER FOR ENGINE TESTING

AFM PARAMETERS

| | | |
|---|---|---|
| Machine | - | Dynetics Production NL60CF-830 |
| Tooling | - | Production Tooling |
| Media | - | Dynetics - D070-20A(61) - 36A(73), - 700(40) |
| Media Temperature | - | 80°F Average |
| Media Pressure | | 150 psi |
| Total Cycles | - | 52 |
| Total Time | - | 95 minutes |

TABLE 56

GEOMETRY AFTER BENCHING AND AFM OR AIRFOILS MILLED WITH PRODUCTION MACHINE ON IMPELLER FOR ENGINE TESTING

| Airfoil and Angular Position | Section Radial Position (Inches) | Contour Deviation Spread (mils) Concave | Convex | Thickness Deviation (mils) Avg | Spread | True Position Deviation (mils) Vert | Horiz |
|---|---|---|---|---|---|---|---|
| Full 0 deg | 2.0 | 3.5 | 1.7 | + 8.4 | 2.0 | 0 | -6.9 |
| | 2.1 | 3.7 | 0 | + 8.8 | 3.9 | 0 | -7.5 |
| | 2.3 | 1.3 | 1.2 | + 8.7 | 2.6 | 0 | -8.3 |
| | 2.5 | 3.1 | 1.8 | + 9.4 | 3.4 | 0 | -7.9 |
| | 2.8 | .8 | .9 | +10.0 | 1.5 | 0 | -2.1 |
| | 3.1 | .9 | 3.6 | + 7.3 | 2.8 | 0 | -1.7 |
| | 3.4 | .2 | 1.4 | +10.6 | 1.4 | 0 | +1.1 |
| | 3.6 | 0 | .3 | +11.9 | .3 | 0 | - .6 |
| | 3.8 | 0 | 1.0 | +10.0 | .2 | 0 | - .8 |
| | 4.0 | 0 | 1.3 | + 9.9 | 1.0 | 0 | 0 |
| | 4.2 | .4 | 1.6 | + 8.6 | 2.1 | 0 | + .6 |
| | 4.4 | .4 | 2.8 | + 9.7 | 2.4 | 0 | 0 |
| First Splitter -8 deg | 2.1 | 2.2 | 1.1 | + 8.1 | 1.1 | 0 | -3.9 |
| | 2.2 | 2.4 | 0 | + 8.0 | 2.8 | 0 | -3.8 |
| | 2.4 | 4.0 | 1.6 | + 6.8 | 2.4 | 0 | -5.1 |
| | 2.6 | 1.3 | .7 | + 7.5 | 1.3 | 0 | -5.7 |
| | 2.8 | .9 | 2.6 | + 8.1 | 2.6 | 0 | -2.4 |
| | 3.1 | .5 | 2.1 | + 5.0 | 1.8 | 0 | -1.9 |
| | 3.4 | 0 | .4 | + 6.4 | .4 | 0 | + .4 |
| | 3.6 | 0 | 0 | + 6.9 | .1 | 0 | + .6 |
| | 3.8 | 0 | .2 | + 5.1 | .1 | 0 | 0 |
| | 4.0 | 0 | 0 | + 4.6 | .8 | 0 | + .6 |
| | 4.2 | 0 | 0 | + 3.9 | .2 | 0 | + .6 |
| | 4.4 | 0 | 0 | + 1.3 | 0 | 0 | +1.4 |
| Second Splitter -16 deg | 2.8 | .8 | 1.7 | + 8.1 | 2.5 | 0 | -2.0 |
| | 2.9 | .9 | 1.3 | + 6.4 | 2.3 | 0 | -2.0 |
| | 3.1 | .6 | 2.5 | + 5.8 | 3.9 | 0 | -1.2 |
| | 3.4 | .3 | 1.2 | + 7.7 | 1.2 | 0 | +1.2 |
| | 3.6 | 0 | 1.3 | + 8.3 | 1.2 | 0 | +1.4 |
| | 3.8 | 0 | 2.1 | + 7.1 | 1.5 | 0 | +1.3 |
| | 4.0 | 1.2 | 1.8 | + 7.1 | 3.5 | 0 | +1.1 |
| | 4.2 | 1.3 | 2.8 | + 5.9 | 3.9 | 0 | +1.9 |
| | 4.4 | 2.4 | 2.3 | + 5.2 | 5.3 | 0 | +1.3 |

NOTES:

Allowable deviations from design nominal:

| | |
|---|---|
| True Position | ±5 mils |
| Contour | ±3 mils |
| Thickness | ±3 to ±6 mils |

TABLE 56 - Continued
GEOMETRY AFTER BENCHING AND AFM OR AIRFOILS MILLED WITH PRODUCTION
MACHINE ON IMPELLER FOR ENGINE TESTING

| Airfoil and Angular Position | Section Radial Position (Inches) | Contour Deviation Spread (mils) | | Thickness Deviation (mils) | | True Position Deviation (mils) | |
|---|---|---|---|---|---|---|---|
| | | Concave | Convex | Avg | Spread | Vert | Horiz |
| Full -72 deg | 2.0 | 1.9 | 2.6 | + 4.2 | .7 | 0 | -4.0 |
| | 2.1 | 3.9 | 1.6 | + 5.7 | 2.6 | 0 | -5.6 |
| | 2.3 | 3.6 | 2.8 | + 6.2 | 2.8 | 0 | -7.6 |
| | 2.5 | 3.4 | 2.0 | + 7.1 | 3.8 | 0 | -6.9 |
| | 2.8 | .7 | .7 | + 7.6 | .2 | 0 | -1.1 |
| | 3.1 | 0 | 3.1 | + 5.4 | 2.7 | 0 | -1.2 |
| | 3.4 | 0 | 1.2 | + 7.1 | 1.7 | 0 | +1.1 |
| | 3.6 | 0 | .7 | + 9.3 | 1.1 | 0 | - .5 |
| | 3.8 | .1 | 1.2 | + 6.2 | 1.5 | 0 | - .3 |
| | 4.0 | 0 | 1.4 | + 6.5 | .8 | 0 | - .7 |
| | 4.2 | 0 | 1.2 | + 5.6 | 1.2 | 0 | - .5 |
| | 4.4 | 1.0 | 1.7 | + 6.7 | 2.7 | 0 | - .8 |
| First Splitter -80 deg | 2.1 | 1.9 | 2.2 | + 9.2 | 4.8 | 0 | -2.1 |
| | 2.2 | 2.1 | 0 | + 8.5 | 2.6 | 0 | -2.8 |
| | 2.4 | 3.7 | .6 | + 6.8 | 2.9 | 0 | -4.6 |
| | 2.6 | 4.4 | 3.1 | + 7.1 | 2.2 | 0 | -4.6 |
| | 2.8 | .2 | 1.9 | + 8.2 | 1.7 | 0 | -1.8 |
| | 3.1 | .4 | 1.8 | + 5.8 | 2.4 | 0 | -1.5 |
| | 3.4 | 0 | .9 | + 6.2 | .4 | 0 | +1.2 |
| | 3.6 | 0 | .4 | + 7.2 | .6 | 0 | + .8 |
| | 3.8 | 0 | 0 | + 4.2 | .3 | 0 | - .2 |
| | 4.0 | 0 | 1.0 | + 5.1 | 1.0 | 0 | 0 |
| | 4.2 | 0 | 1.1 | + 4.5 | 1.1 | 0 | 0 |
| | 4.4 | 0 | .6 | + 3.0 | 0 | 0 | 0 |
| Second Splitter -88 deg | 2.8 | .8 | 3.0 | + 6.8 | 3.5 | 0 | -1.3 |
| | 2.9 | .6 | 3.1 | + 5.9 | 3.9 | 0 | -1.7 |
| | 3.1 | 0 | 4.1 | + 5.2 | 3.4 | 0 | -1.6 |
| | 3.4 | 0 | 2.5 | + 5.6 | 2.8 | 0 | + .6 |
| | 3.6 | 0 | 2.4 | + 6.9 | 2.9 | 0 | + .3 |
| | 3.8 | .1 | 2.1 | + 5.8 | 3.6 | 0 | - .9 |
| | 4.0 | 1.7 | 3.0 | + 5.2 | 3.9 | 0 | - .4 |
| | 4.2 | 2.3 | 3.4 | + 5.2 | 6.0 | 0 | -1.7 |
| | 4.4 | 1.8 | 3.1 | + 4.5 | 4.1 | 0 | -1.3 |

TABLE 56 - Continued
GEOMETRY AFTER BENCHING AND AFM OR AIRFOILS MILLED WITH PRODUCTION MACHINE ON IMPELLER FOR ENGINE TESTING

| Airfoil and Angular Position | Section Radial Position (Inches) | Contour Deviation Spread (mils) Concave | Contour Deviation Spread (mils) Convex | Thickness Deviation (mils) Avg | Thickness Deviation (mils) Spread | True Position Deviation (mils) Vert | True Position Deviation (mils) Horiz |
|---|---|---|---|---|---|---|---|
| Full -168 deg | 2.0 | 2.9 | 3.0 | + 6.3 | 2.7 | 0 | -5.8 |
| | 2.1 | 2.5 | .8 | + 6.4 | 2.6 | 0 | -7.9 |
| | 2.3 | 3.5 | 2.2 | + 5.7 | 2.4 | 0 | -8.3 |
| | 2.5 | 4.8 | 3.1 | + 6.0 | 3.9 | 0 | -8.4 |
| | 2.8 | .2 | 1.3 | + 6.6 | .8 | 0 | -3.9 |
| | 3.1 | 0 | 4.4 | + 6.8 | 4.5 | 0 | -5.0 |
| | 3.4 | .1 | 2.0 | + 7.0 | 2.6 | 0 | -2.4 |
| | 3.6 | .6 | 2.7 | + 8.5 | 3.2 | 0 | -3.1 |
| | 3.8 | 1.5 | 2.8 | + 8.6 | 4.3 | 0 | -4.3 |
| | 4.0 | 1.2 | 2.4 | + 7.3 | 4.1 | 0 | -4.9 |
| | 4.2 | .9 | 1.9 | + 5.8 | 3.6 | 0 | -4.9 |
| | 4.4 | 2.1 | 3.8 | + 7.3 | 6.2 | 0 | -6.0 |
| First Splitter -176 deg | 2.1 | 2.1 | 2.3 | + 8.6 | 5.7 | 0 | -5.7 |
| | 2.2 | 2.4 | .1 | + 8.8 | 2.5 | 0 | -7.5 |
| | 2.4 | 2.3 | .3 | + 7.9 | 2.5 | 0 | -7.0 |
| | 2.6 | 4.1 | 2.3 | + 8.6 | 3.1 | 0 | -7.1 |
| | 2.8 | .9 | .6 | + 8.1 | 2.3 | 0 | -5.0 |
| | 3.1 | .3 | 1.4 | + 6.7 | 1.3 | 0 | -5.7 |
| | 3.4 | 0 | 1.0 | + 7.1 | 1.5 | 0 | -3.6 |
| | 3.6 | 0 | 0 | + 7.6 | .1 | 0 | -3.3 |
| | 3.8 | 0 | .2 | + 7.3 | .6 | 0 | -4.3 |
| | 4.0 | 0 | .4 | + 6.8 | .3 | 0 | -2.8 |
| | 4.2 | 0 | .5 | + 5.4 | .8 | 0 | -4.8 |
| | 4.4 | 0 | 0 | + 3.4 | 0 | 0 | -5.1 |
| Second Splitter -184 deg | 2.8 | .8 | 3.4 | + 8.2 | 3.7 | 0 | -5.0 |
| | 2.9 | .6 | 3.0 | + 7.3 | 4.7 | 0 | -3.5 |
| | 3.1 | 0 | 3.7 | + 6.8 | 3.9 | 0 | -4.1 |
| | 3.4 | 0 | 3.6 | + 7.4 | 4.0 | 0 | -3.3 |
| | 3.6 | 0 | 2.8 | + 8.0 | 2.7 | 0 | -2.8 |
| | 3.8 | 0 | 3.7 | + 7.1 | 4.5 | 0 | -4.4 |
| | 4.0 | 1.2 | 3.6 | + 7.1 | 5.6 | 0 | -5.0 |
| | 4.2 | 2.4 | 4.1 | + 6.9 | 6.7 | 0 | -4.3 |
| | 4.4 | 3.0 | 4.0 | + 5.5 | 6.5 | 0 | -4.6 |

TABLE 57

GEOMETRY AFTER BENCHING AND AFM OF TYPICAL AIRFOILS MILLED WITH PRODUCTION MACHINE ON IMPELLER FOR ENGINE TESTING

(T700 Impeller Airfoil Inspection)

Part: Impeller - After AFM     Serial No: GLB83193     Date: 10/18/78     Tech: J.D.

Airfoil: Full Blade     Airfoil Pos: -72°     True Pos Offset: .0894 .0907 AF=0

| Chart No. | Sect W | Sta | Thickness Limits (in) | Thickness Actual (mils) | Thickness Out of Limits (mils) | Contour Limits ±3 (mils) Actual Left | Actual Right | Out of Limits Left | Out of Limits Right | Best Fit Contour (mils) Ang | Left Vert | Left Hor | Right Vert | Right Hor | True Pos. Vert | True Pos. Hor |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | ±.003 | +4.3 | +1.3 | -1.3 | + .7 | OK | OK | 0° | 0 | .6 | 0 | 8.8 | 0 | 4.0 |
| | 2.0 | 2 | ±.003 | +4.5 | +1.5 | - .5 | + .5 | | | | | | | | | |
| | | 3 | ±.003 | +3.8 | + .8 | + .6 | -1.9 | | | | | | | | | |
| 1 | | 1 | ±.006 | +7.7 | +1.7 | + .8 | - .6 | OK | OK | 0° | 0 | 4.3 | 0 | 7.4 | 0 | 1.1 |
| | 2.8 | 2 | ±.006 | +7.6 | +1.6 | + .8 | - .9 | | | | | | | | | |
| | | 3 | ±.006 | +7.5 | +1.5 | + .1 | - .2 | | | | | | | | | |
| | | 1 | ±.006 | +8.7 | +2.7 | 0 | - .2 | OK | OK | 0° | 0 | 6.9 | 0 | 6.1 | 0 | .5 |
| | 3.6 | 2 | ±.006 | +4.8 | OK | 0 | + .5 | | | | | | | | | |
| | | 1 | ±.003 | +4.7 | +1.7 | -2.2 | + .7 | OK | OK | 0° | 0 | 0 | 0 | 10.9 | 0 | 5.6 |
| | 2.1 | 2 | ±.003 | +5.2 | +2.2 | - .5 | - .9 | | | | | | | | | |
| | | 3 | ±.003 | +7.3 | +4.3 | +1.7 | - .6 | | | | | | | | | |
| 2 | | 1 | ±.006 | +3.8 | OK | 0 | -1.7 | OK | OK | 0° | 0 | 3.1 | 0 | 6.8 | 0 | 1.2 |
| | 3.1 | 2 | ±.006 | +5.8 | OK | 0 | + .6 | | | | | | | | | |
| | | 3 | ±.006 | +6.5 | + .5 | 0 | +1.4 | | | | | | | | | |
| | | 1 | ±.0035 | +6.1 | +2.6 | 0 | - .6 | OK | OK | 0° | 0 | 4.8 | 0 | 6.5 | 0 | .7 |
| | 4.0 | 2 | ±.0035 | +6.9 | +3.4 | 0 | + .8 | | | | | | | | | |

TABLE 58

GEOMETRY AFTER BENCHING AND AFM OF TYPICAL AIRFOILS MILLED WITH PRODUCTION MACHINE ON IMPELLER FOR ENGINE TESTING

| Measurement Radial Location | Contour Deviation from Nominal (mils) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Flow Path Angular Location | | | | | | | | | | | |
| (Inches) | 0° | -8° | -16° | -72° | -80° | -88° | -168° | -176° | -184° | -240° | -248° | -256° |
| 1.8925 | +4.4 | +1.7 | +1.1 | +5.6 | +3.4 | +0.6 | +5.3 | +5.2 | +2.3 | +3.1 | +1.6 | +1.3 |
| 1.8918 | -2.6 | -0.9 | -0.5 | -0.2 | -0.6 | +0.9 | 0 | +1.4 | +2.7 | -0.7 | -0.6 | -0.2 |
| 1.9143 | -5.5 | 0 | -0.2 | +0.9 | +0.1 | +1.1 | -2.1 | +2.3 | +3.4 | -3.1 | -0.4 | -0.8 |
| 2.0281 | -4.5 | -0.9 | +2.9 | -6.3 | -3.1 | +2.7 | -4.1 | +1.5 | +4.3 | -2.7 | -3.2 | -0.3 |
| 2.1971 | -2.9 | -3.4 | +0.1 | -4.2 | -2.2 | -3.0 | -1.0 | -0.1 | +3.8 | -0.7 | -3.4 | +1.8 |
| 2.7124 | -3.8 | -3.2 | -4.0 | -3.4 | -1.7 | -2.2 | -2.7 | -0.7 | -1.5 | -2.3 | -2.2 | -3.3 |
| 3.2737 | -2.6 | -2.0 | -1.5 | -2.5 | -1.0 | -1.2 | -2.2 | +0.1 | +0.1 | -1.2 | -1.2 | -1.6 |
| 3.7290 | -3.3 | -2.8 | -4.0 | -3.9 | -2.2 | -3.1 | -3.1 | +0.6 | -2.2 | -1.6 | -1.8 | -2.8 |
| 4.1612 | -3.3 | -3.3 | -3.7 | -4.1 | -2.4 | -3.3 | -3.7 | -1.9 | -2.7 | -2.0 | -2.5 | -3.2 |
| 4.5698 | -2.5 | -2.7 | -3.8 | -3.1 | -2.0 | -2.7 | -2.4 | -0.7 | -2.2 | -1.8 | -1.7 | -2.8 |

NOTES:

Design limits are ±3mils from nominal
Flow path clockwise from airfoil facing leading edge has the same number as the airfoil.

## TABLE 59
## STATISTICAL ANALYSIS OF THICKNESS MEASUREMENTS OF FULL AIRFOILS, FIRST SPLITTERS, AND SECOND SPLITTERS MILLED WITH PRODUCTION MACHINE ON IMPELLER FOR ENGINE TESTING

FULL AIRFOIL

| | | |
|---|---|---|
| Mean | = | +7.84 mils |
| Std Dev | = | 1.59 mils |
| Sample | = | 28 measurements |

FIRST SPLITTER

| | | |
|---|---|---|
| Mean | = | +6.51 mils |
| Std Dev | = | 1.81 mils |
| Sample | = | 116 measurements |

SECOND SPLITTER

| | | |
|---|---|---|
| Mean | = | +6.26 mils |
| Std Dev | = | 1.99 mils |
| Sample | = | 76 measurements |

ALL AIRFOILS

| | | |
|---|---|---|
| Mean | = | + 6.97 mils |
| Std Dev | = | 2.15 mils |
| Sample | = | 320 measurements |

NOTE

Thickness Tolerance ±3.0 to ±6.0 mils

TABLE 60
STATISTICAL ANALYSIS OF TRUE POSITION MEASUREMENTS OF FULL AIRFOILS, FIRST SPLITTERS, AND SECOND SPLITTERS MILLED WITH PRODUCTION MACHINE ON IMPELLER FOR ENGINE TESTING

FULL AIRFOIL

| | | |
|---|---|---|
| Mean | = | 0 mils vertical, -4.34 mils horizontal |
| Std Dev | = | 2.67 mils |
| Sample | = | 48 measurements |

FIRST SPLITTER

| | | |
|---|---|---|
| Mean | = | 0 mils vertical, -3.21 mils horizontal |
| Std Dev | = | 1.91 mils |
| Sample | = | 48 measurements |

SECOND SPLITTER

| | | |
|---|---|---|
| Mean | = | 0 mils vertical, -2.12 mils horizontal |
| Std Dev | = | .97 mils |
| Sample | = | 36 measurements |

ALL AIRFOILS

| | | |
|---|---|---|
| Mean | = | 0 mils vertical, -3.32 mils horizontal |
| Std Dev | = | 2.92 mils |
| Sample | = | 132 measurements |

NOTE:

True Position Tolerance $\pm 5.0$ mils

TABLE 61

STATISTICAL ANALYSIS OF THICKNESS MEASUREMENTS OF FULL AIRFOILS, FIRST SPLITTERS, AND SECOND SPLITTERS MILLED WITH PRODUCTION AND DEVELOPMENT MACHINES ON IMPELLER BLANK

FULL AIRFOIL

| | | |
|---|---|---|
| Mean | = | +3.68 mils |
| Std Dev | = | 2.80 mils |
| Sample | = | 55 measurements |

FIRST SPLITTER

| | | |
|---|---|---|
| Mean | = | +.58 mils |
| Std Dev | = | 2.56 mils |
| Sample | = | 59 measurements |

SECOND SPLITTER

| | | |
|---|---|---|
| Mean | = | +.63 mils |
| Std Dev | = | 1.86 mils |
| Sample | = | 36 measurements |

ALL AIRFOILS

| | | |
|---|---|---|
| Mean | = | +1.72 mils |
| Std Dev | = | 2.90 mils |
| Sample | = | 150 measurements |

NOTE:

Thickness Tolerance ±3.0 to ±6.0 mils

Step No:

Roughed
1. 15 Area A's
2. 15 Area B's
3. 45 Area C's
4. 15 Area F's
5. 15 Area G's
6. 15 Area H's

Hub Roughed
7. 15 Area A's
8. 45 Area C's

Finished Leading Edge
9. 15 Second Splitters
10. 15 First Splitters

Finished
11. 15 First Splitters
12. 15 Second Splitters

Hub Finished
13. 15 Area G's
14. 15 Area H's

Finished Leading Edge
15. 15 Full Blade

Finished
16. 15 Full Blades

Hub Finished
17. 45 Area C's
18. 15 Area A's
19. 15 Area B's
20. 15 Area F's
21. 15 Area G's
22. 15 Area H's

Fillet Finished
23. 15 First Splitters
24. 15 Full Blades
25. 15 Second Splitters

NC Program Time
Section of 3 airfoils and hub areas and fillets
7 hrs: 11 min.

Number of Cutters Used
5/16 Airfoil Rough - 17
3/16 Airfoil and Hub Rough------- 45
5/16 L.E. Finish --- 2
1/8 Fillet Finish -- 13

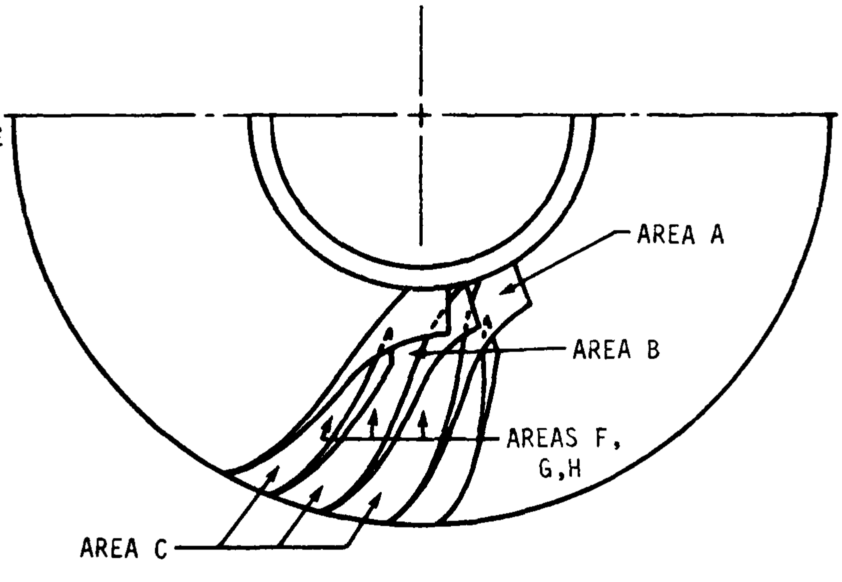



Figure 150. Procedure for Milling Airfoils and Hubs with Production Machine (Impeller for Engine Testing).

T700 IMPELLER DEVELOPMENT INSPECTION

AIRFOIL SURFACE ROUGHNESS

SERIAL NO: GLB83193 INSP BY: WWG DATE: 10-3-78

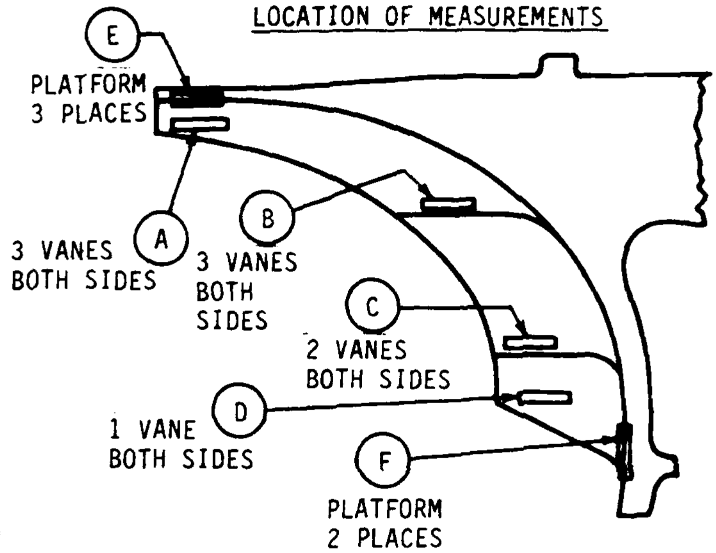
SETUP AND INSPECT PER WI MG 6 1978 USING PROFILOMETER

DRAWING REQUIREMENTS

$^{32}\sqrt{\ }$ on airfoils and platform (Ref Sect JJ, Zone A-13)

Drg. Note 10: "Surface Finish Requirements Apply Before Peening"

LOCATION OF MEASUREMENTS




| | AIRFOILS | | | | HUB | |
|---|---|---|---|---|---|---|
| PRESSURE SIDE | A | B | C | D | E | F |
| -168° Full Vane | 24 | 22 | 22 | 37 | 15 | 43 |
| -176° Splitter | 8 | 17 | 17 | -- | 25 | -- |
| -184° Half Splitter | 11 | 18 | -- | -- | 16 | -- |
| SUCTION SIDE | | | | | | |
| -168° Full Vane | 14 | 16 | 15 | 17 | -- | 60 |
| 176° Full Vane | 6 | 20 | 32 | -- | -- | -- |
| -184° Half Splitter | 10 | 22 | -- | -- | -- | -- |

COMMENTS

Hub surface roughness being reduced by additional benching.

All numbers are microinches average amplitude except as noted.

* "Pressure Side" is the left-hand side of an airfoil looking aft.

Figure 151. Surface Roughness After Benching and AFM of Airfoil and Hub Surfaces Milled With Production Machine on Impeller for Engine Testing.

ECONOMICS

VIBRATION AND ENGINE TESTS

CONCLUSIONS AND RECOMMENDATIONS

## ECONOMICS

### LABOR

Labor required to produce the first year of production blisks and impeller with the airfoil manufacturing system developed under this program is less than the labor specified in the objectives established before the program began. Labor objectives were established for each blisk and impeller and were based on starting production in a completely new manufacturing facility, planned around the airfoil manufacturing system.

The actual labor required to produce the first 200 components is compared with the labor objectives from them in Table 62 (pg 296). This comparison indicates 35% less actual labor than the program objective for the first year of production. Actual labor includes all of the direct labor required to produce complete components, including the labor required to machine airfoils. All of the direct labor learning effects of starting production in a completely new facility, with new tools, new methods, and new processes are reflected in the actual labor data.

Performance was better than the objectives for the following reasons:

1. The new facility was carefully planned and the equipment selected was capable of meeting all manufacturing requirements. In particular, the production four-spindle, five-axis contour NC milling machine maintained airfoil dimensions within close tolerances during all machining conditions, was capable of operating at the highest required cutting parameters and performed essentially without malfunction.

2. The development program for the airfoil manufacturing system was designed to be a production turn key system. All of the manufacturing process instructions, tooling, fixturing, and NC programs, used to manufacture the qualification hardware were designed to be used in production.

3. Transition of the airfoil manufacturing system from development to production was also carefully planned. The manufacturing and programming specialists were transferred to the new facility with the system they developed. As a result, the transition to production was very efficient, even though the new system was based on advanced and complex technology.

4. The cost of the first year of production reflected a cost that would be expected of a non-unique production start-up as a result of the process development program and its successful transition into production. Much of the anticipated learning came during the development program and resulted in a high learning curve value for the first year of production. It is anticipated that the actual versus forcasted labor curves will converge as the 250th engine set of components is manufactured.

TABLE 62

COMPARISON OF LABOR OBJECTIVES WITH ACTUAL LABOR REQUIRED TO PRODUCE COMPLETE BLISKS AND IMPELLERS USING THE NEW MANUFACTURING SYSTEM

| Component | Components Manufactured | Program Objective Labor per Component (Avg Hrs) | Actual Labor Per Component (Avg Hrs) | Actual Labor Per Component as Percentage of Program Objectives (%) |
|---|---|---|---|---|
| Stage 1 Blisk | 41 | 138 | 96 | 70 |
| Stage 2 Blisk | 66 | 83 | 55 | 66 |
| Stage 3 and 4 Blisk | 41 | 166 | 122 | 73 |
| Stage 5 Blisk | 40 | 88 | 65 | 74 |
| Impeller | 12 | 337 | 186 | 55 |

COST REDUCTION

The estimated shop cost of producing a complete engine set of blisks and impellers in the new manufacturing facility, with the system developed under this program, is approximately $10,000 less than the cost of producing a set with previously available processes. This is equivalent to a cost reduction of approximately 60 percent. This reduction was accomplished through increased labor productivity made possible by the use of advanced technology.

SAVINGS

The cost, to the Department of Denfense, of engines with blisks and impellers produced with the new system is approximately $15,000 less than was previously possible. More than 4000 engines are planned for production with the new system; therefore, this development program will result in savings of more than $60 million.

The cost of the development program to the Army's Aviation Research and Development Command was approximately $1.4 million. Consequently, the return on investment of AVRADCOM Manufacturing Methods and Technology funds is projected to be more than 40 to 1.

New manufacturing equipment, capable of meeting specifications developed under the program was needed to apply the new system to production engine manufacture. A total of approximately $10.9 million was supplied by the Army's Troop Support and Aviation Material Readiness Command for this essential equipment, so that the projected savings could be realized.

# VIBRATION AND ENGINE TESTS

## PURPOSE OF TESTS

Tests were conducted to assure that airfoils produced with the processes developed under this program would meet engine operating requirements.

## VIBRATION TESTS

Vibration tests were conducted in the laboratory to determine the fatigue strength, natural frequencies, and nodal patterns of airfoils for all five blisk stages and the impeller, which were produced with manufacturing processes developed under this program.

Test results showed that the fatigue strength and vibration characteristics of airfoils produced with the newly developed processes, are similar to the fatigue strength and vibration characteristics of airfoils produced with previously available processes, which have extensive service in engines.

Therefore, it was concluded that airfoils produced with the new processes should operate in engines without mechanical problems.

## ENGINE TESTS

Engine tests were conducted to assess the aerodynamic performance of airfoils produced with the newly developed processes, and to verify their mechanical integrity. Three engine builds were used for the tests. All of the tests were successful. Significant results of the tests are summarized below.

Stage 1 and Stage 2 Blisks were tested in Engine Serial No. 20701602. An improved airflow characteristic was found, which was attributed to excellent leading edge contour and thickness. In addition, an improvement of approximately 5° to 10°F in deceleration stall temperature margin was found, which was also attributed to improved airfoil quality.

All five blisk stages were tested in Engine Serial No. 212103-1A. The engine was operated over the Idle to Maximum power range, in 50 rpm speed increments, for 10 minutes at each increment. Consequently, the airfoils were subjected to all vibratory modes, for at least $10^6$ cycles. No mechanical problems were encountered. This demonstrated the mechanical integrity of the airfoils.

All five blisks and the impeller were tested in Engine Serial No. 207011-15. Tests were run like those above except that speed was held for 5 minutes at each increment. Again no mechanical problems were encountered, further demonstrating the mechanical integrity of the airfoils.

These tests indicated improved aerodynamic performance of airfoils produced with the new processes. However, additional tests with a substantial number of blisks and impellers, produced over a period of time in the new manufacturing facility, are needed to substantiate improved performance, and to accurately define the magnitude of the improvement.

## CONCLUSIONS AND RESULTS

The Blisk and Impeller Process Development Program has led to some important gains in manufacturing capabilities. Combining these advanced processes into a complete airfoil manufacturing system, resulted in major savings in time over conventional processes with a commensurate savings in labor costs.

The program produced the following results:

1. Manufacturing cost reduction of 60 percent per engine set.

2. Projected program savings of more than $60 million.

3. Transferable technology; Well-suited to high volume, high-precision, cost sensitive manufacturing programs.

4. Technology base for CAD/CAM airfoil manufacturing.

Other benefits from this program are:

1. Airfoils conform closely to design requirements and are more uniform than airfoils produced by the previous processes.

2. Important improvement in engine performance obtained, compared with parts produced by previous processes.

3. All critical manual operations eliminated.

4. Manufacturing cost objectives met.

5. Production began on schedule without startup difficulties, in a completely new manufacturing facility incorporating the system developed under this program.

## RECOMMENDATIONS

Work done in the course of this program indicated that there is opportunity to substantially increase the life of the cutters used to contour mill airfoils This would result in significant savings. Therefore, it is recommended that a program be conducted to double the useful life of cutters.

# APPENDIX A

## SPECIFICATION FOR PRODUCTION FIVE-AXIS, FOUR SPINDLE COMPUTER NUMERICALLY CONTROLLED CONTOUR MILLING MACHINE

Specification No. EE-183-3
Page 1 of 24
Date May 3, 1979

# FACILITY DESCRIPTION

Five (5) Axis Numerically
Controlled Contour Milling Machine

## FACILITY LOCATION

Hooksett, New Hampshire - Plant II
Government Procurement

Approved by:

W. A. Watson, Jr.
Facilities Engineer
T700 Blisks/Impeller Operation
Plant II - Hooksett, NH
Phone: (603)669-4900 Ext. 258

Approved by:

R. L. Yeaton, Manager
T700 Blisks/Impeller
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Plant II - Hooksett, NH
Phone: (603)669-4900 Ext. 278

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP
HOOKSETT, NEW HAMPSHIRE 03106

1.0 GENERAL

1.1 Scope

This specification covers the manufacture, inspection, performance and installation requirements for a five (5) axis multi-spindle numerically controlled contour milling machine.

1.2 Instructions for Quoting

1.2.1 The vendor shall quote his standard equipment and related accessories.

1.2.2 If vendor's standard equipment does not conform to any of the requirements listed here, he shall:

1.2.2.1 Quote his standard equipment and accessories.
1.2.2.2 Indicate how the standard machine does not conform.
1.2.2.3 Quote additional price of modifying the standard equipment to comply with this specification. Also state percentages of the additional price which are applicable to Engineering, Materials and Manufacturing.

1.2.3 The vendor's quotation must state compliance with this specification. Some exceptions to this specification may be approved by the customer, therefore, exceptions must be detailed in the vendor's quotation with reference to the paragraph involved.

1.2.4 The vendor shall submit with his quotation, a completed General Electric "Data Form #DF-10" which will be considered preliminary until resubmitted in accordance with Paragraph 5.1.1.

1.2.5 The vendor's quotation shall include delivery time of entire equipment package and shall be based on arrival at the designated General Electric Company Plant.

1.3 Responsibilities of the Vendor

1.3.1 The successful vendor shall be responsible for ensuring that the equipment supplied to the customer fully complies with the requirements of this specification including any deviations accepted by the General Electric Company as referenced in Paragraph 1.2.3.

1.3.2 The equipment described herein shall be built to customer approved drawings. Customer approval of any document describing a design, process, or procedure does not waive or supersede any of the requirements of this specification nor the vendor's responsibility for fulfilling all of the specification requirements.

## 2.0 APPLICABLE DOCUMENTS

The following documents shall form a part of this specification. Any exceptions shall be stated in the vendor's quotation. In cases where General Electric and other codes conflict, General Electric requirements shall apply.

2.1 General Electric Specification for the Electrification of Machine Tools and Industrial Equipment No. S1231-06, dated 10/30/72. When the purchase order references a Government Contract number, the requirements for exclusive use of General Electric components, is waived.

2.2 General Electric Specification for Electronic Industrial Equipment No. S1231-07, dated 3/1/71.

2.3 General Electric Specification S1251-01, dated 12/31/68. (Electrical Grounding)

2.4 General Electric Specification S1251-20, dated 11/28/72. (Color Coding)

2.5 General Electric "Installation Data" Form No. DF-10, dated 3/24/69.

2.6 National Electric Code NFPA #70 (Latest Edition).

2.0 APPLICABLE DOCUMENTS (Cont'd.)

2.7 The latest revision of the Joint Industrial Council's Electrical Standards for General Purpose Machine Tools.

2.8 The latest revision of the Joint Industrial Council's Hydraulic Standards.

2.9 National Machine Tool Builders Association (NMTBA) Standard.

2.10 The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section VIII.

2.11 Applicable portions of the latest edition of the U.S. Department of Labor (Safety & Health Standards) - commonly known as (O.S.H.A.).

3.0 REQUIREMENTS

3.1 General

3.1.1 The basic machine tool configuration shall be a design, consistent with the supplier's own manufacturing standards and construction, unless otherwise required by this specification.

3.1.2 The machining center shall contain five (5) axis of motion, capable of performing simultaneous contour milling operations, utilizing all axes under numerical control. It will consist of a completely integrated machining system, which is to include:

a. Linear longitudinal motion (X - axis)
b. Linear transverse motion (Y - axis)
c. Linear vertical motion (Z - axis)
d. Indexing and rotary motion (B - axis)
e. Tilting motion (A - axis)

**Axis nomenclature to be in accordance with EIA designations in the event of conflict.**

SE 1316-B

3.0 REQUIREMENTS (Cont'd.)

3.1.3 Servo Drives for all five (5) axes will be actuated by hi-gain, closed loop, positioning and velocity feedback systems. Low-speed, high-torque d.c. electric motors will be coupled directly to their respective feed screws to minimize the presence of reverse-motion loss and inertia. Gain (servo lag) will be calibrated to yield the minimum obtainable error in following consistent with overall system stability.

3.1.4 A General Electric Mark Century 1050 numerical contouring control system shall simultaneously control the longitudinal, transverse, vertical, tilting and rotational movements of the machine.

3.1.5 The machine shall be capable of machining the complex airfoil and platform configuration to the close tolerances of the following part drawing numbers:

| | | |
|---|---|---|
| Blisk stage 1 | - 6032T26 | |
| Blisk stage 2 | - 6032T27 | |
| Blisk stage 3 & 4 | - 6038T08 | (Integral) |
| Blisk stage 5 | - 6038T09 | |
| Impeller | - 6038T74 | |

3.1.6 The overall construction and design shall be sufficiently rugged to be able to take heavy, accurate roughing cuts free from chatter and vibration, when rough machining metal parts at rated horsepower using proper tools, speeds and feeds. It shall also provide the ability to take very fast and accurate finish cuts, to a smooth finish at proper speeds and feeds, using properly sharpened and prepared tools. The maximum floorspace requirement of the installed 5A/4S machining center shall not exceed 16' x 16'. The operator working space shall not exceed 10' x 5'. The maximum erected height of the machine, including any shields or access covers in the closed or open positions, shall not exceed 11' 6".

SE 1316-B

3.0 REQUIREMENTS (Cont'd.)

3.1.7 The machine shall be provided with a "home" or initial position, controlled by high accuracy limit switches. Depressing the initial position button (control) will cause the slides to move automatically to their respective "home" positions. An indicator light (control) will detect when home position has been attained. Unless otherwise indicated, home position dimensions will be:

| | | |
|---|---|---|
| Longitudinal Slide | (X-axis) | 6.0000" |
| Transverse Slide | (Y-axis) | 10.0000" |
| Vertical Slide | (Z-axis) | 0.0000" |
| Work Piece Carrier Tilt | (A-axis) | -10° |
| Work Piece Carrier Rotation | (B-axis) | 0 |

Sequence of Moves: Z-Y-X-A-B

3.1.8 All Linear Slides will be controlled by precision hardened and ground ways. Supported members will be lined with phenolic wear strips, or their equivalent, bonded to their guiding surfaces. Does not apply if hydrostatic ways are to be supplied.

3.2 Safety Devices

3.2.1 The machine shall be fitted with suitable safety devices of the latest approved type for covering all movable parts, and electrical connections that may cause injury to the operator. All safety devices shall comply with the laws of the state of New Hampshire and Massachusetts.

3.2.2. The safety devices shall include machinery guards, electrical control interlocking switches, fuses and door safety switches, etc.

3.2.3 All safety devices and guards shall be easy to mount and dismount for making adjustments.

3.0 REQUIREMENTS (Cont'd.)

3.2.4 All control cabinets, motors, metal conduits, control stations and other areas shall be grounded in accordance with General Electric Specification S1251-01.

3.2.5 The machine noise level (excluding tool noise) shall not exceed 83 decibels along the immediate perimeter of the machine tool proper and major sub-systems, when operating at any of the available speeds or feeds. Any dampening shields or covers shall not interfere with normal operation of machine.

3.2.6 The machine shall be provided with "overtravel" limiting devices (limit switches) such that the slides cannot travel beyond their normal operating range and cause damage to the machine or its components.

3.3 Adjustment-Interchangeable Parts

3.3.1 The design of the machine shall permit adjustment for wear of important components. Adjustment or replacement of all parts subject to wear shall be readily accessible.

3.3.2 All replaceable parts shall be manufactured to definite standards for tolerance, clearance and finish, so they may be field installed without further machining.

3.3.3 Machine and Control System Components, which are not manufactured by the contractor, but are available from other commercial sources, shall be identified in the parts list with the sub-contractor or supplier's name and part identification number.

3.4 Bed Column Table Base

3.4.1 The bed and column shall be made from high grade cast iron, and having sufficient heavy crosswebbing to fully resist all machine and cutter forces to which it may be subjected. The bed shall provide leveling screws which make provision for through holes for fastening to the floor or foundation surface.

3.0 REQUIREMENTS (Cont'd.)

3.4.2 The table base shall be accurately precision fitted to the bed, and shall carry hardened and precision ground ways for the work table motion(s).

3.4.3 The bearings for the precision ball screws, for vertical, longitudinal, and transverse motion shall be permanently mounted, aligned and doweled to the respective assemblies, for permanent insurance of mutual perpendicularity.

3.5 Table

3.5.1 The work table shall be machined from high grade cast iron and shall be of sufficient stiffness, weight and strength to support the heaviest workpieces (including carriers and fixtures) which can be milled within the machine's designed capacity.

3.5.2 The table shall be so fitted to the table base as to eliminate gibs, yet provide permanent alignment through accurate truncated-vee ways (or their equivalent) and hold-down straps properly fitted, to prevent lifting of table under heavy cuts, using phenolic way material on the straps.

3.5.3 The table shall be provided with full support over its total working range.

3.6 Cross Slide

3.6.1 The cross slide, shall be captured on either side by large dovetails or square lock ways, in heavy cross slide support castings.

3.6.2. The cross slide support castings shall extend over work area in such a manner as to provide full support to the cross slide in its full forward position just as in retracted position, thus preventing sag and lifting from cutter forces when slide is in extended position.

SE 1316-B

3.0 REQUIREMENTS (Cont'd.)

3.6.3 The spindle head and spindles shall be carried so as to be fully supported so that all spindles shall be equally free from vibration and chatter.

3.6.4 One of the two cross-slide support castings shall be arranged for adjustment for easy take-up for wear, or for refitting after any future rescraping operation.

3.7 Linear Transverse Slide (Y Axis)

3.7.1 The linear transverse slide will be supported by a heavy fine grained cast iron structure, and captured in large dovetails or square lock ways.

3.7.2 The linear transverse slide will carry the four (4) spindle head assemblies and their respective drive motors.

3.8 Spindles

3.8.1 The machine shall have four (4) spindle assemblies mounted on the linear transverse slide, at a minimum center distance of eleven (11) inches.

3.8.2 The spindles will be ground with a number forty (40) milling machine internal taper or approved equivalent interface as an integral part of the spindle configuration. A power operated draw bar will be provided to secure the tool shanks to the spindles for tapered spindle configurations with an appropriate safety device to assure tool holder containment at high RPM. If an alternate tool holder design is used, tool holders for each spindle plus one spare must be included in the base machine price.

3.8.3 Dynamic spindle braking shall be provided.

3.8.4 External means of temperature control utilizing a refrigerated circulatory system(s) shall be provided to prevent bearing overtemperature, minimize spindle growth and maintain required coolant temperature.

3.0 REQUIREMENTS (Cont'd.)

3.8.5 Spindle Speeds will be infinitely variable by tape control within the total speed range. If more than a single speed range is required, range shifting may be accomplished by either tape control or a manually actuated control device. Manual belt change to accomplish range shifting is not allowed. Speed regulation will not exceed two (2) percent variation between any of the four (4) spindles.

3.8.6 Spindle Speeds will be tape controlled with manually preset capability. The necessary potentiometers and speed indicators shall be provided to display actual RPM. A feedback system shall be provided to prevent an overspeed condition.

3.8.7 Spindle Load will be monitored by conveniently installed meters. Each spindle/motor will be provided with its own load meter. A dial or digital type load meter, to show percentage of total available load, having a 0 to 150% load range and 2% resolution, will be provided.

3.9 Coolant System

3.9.1 The machine shall be equipped with a flood and spray mist cutter coolant system.

3.9.2 The coolant system shall be provided with valves for regulating or discontinuing the flow of coolant at the point of discharge. The coolant system provided shall include all necessary piping, valves, nozzles, filters, tank or reservoir, pumps, motor, etc. The coolant pump shall be accessibly located, with convenient means for disengagement. Coolant on/off to be by tape control.

3.9.3 Heat Exchanger for Coolant Supply shall be supplied to control coolant temperature within $\pm$ 5° F of ambient. Water will not be used as a heat transfer medium.

3.9.4 Mist Hood and Collector shall be supplied to confine vaporized coolant and coolant spray to the immediate machine area.

3.0 REQUIREMENTS (Cont'd.)

3.9.5 Chip Separator System shall be defined at time of request for quote.

3.9.6 Coolant containment is required for the coolant pumping unit and machine cutting areas to negate the need for drip pans on or near the machine tool proper.

3.10 Machine Protection

3.10.1 The machining center shall incorporate safety devices to stop all motion of X, Y, Z, A and B axes, while simultaneously initiating an automatic Z axis retract cycle. The operator shall be able to restart the machine immediately without an imposed warm-up delay.

3.10.2 All machine slides shall be provided with way wipers. All ball screws shall be provided with protective covers. The X axis slide way shall be provided with telescoping metal covers.

3.10.3 The machine and controls shall be provided with full protection against contamination by water or oil base coolants.

3.10.4 The equipment shall have an automatic lubrication system for all sliding and rotating components requiring lubrication. The system shall distribute the appropriate amount of lubrication in the required areas.

3.10.4.1 Where lubrication failure could cause immediate damage to the machine, automatic safety devices shall be incorporated which will prevent such damage. A red warning light will indicate the presence of such failure. In the event of a "safe stop" condition caused by lube failure, Z axis shall automatically "retract" to home position.

3.0 REQUIREMENTS (Cont'd.)

3.10.4.2 All lubrication reservoirs shall be equipped with visual level indicators and all filler caps and other lubrication points shall be identified as to the type of lubricant used. General Electric Company shall have the option of substituting a lubricant equivalent to the type specified by the vendor.

3.10.4.3 Lubrication reservoir capacity shall be sufficient for a minimum of 80 hours of machine operating time when adjusted in accordance with the vendor's recommendations.

3.10.5 A Z axis "retract" cycle shall be automatically initiated subject to all safe stop/emergency stop conditions to include but not limited to: control off, air loss, safety limit switch engaged and coolant failure.

3.10.5.1 Z axis shall be provided with a "positive release on power" clamping device which shall automatically clamp the Z axis to prevent any downward motion in the event of a power failure.

3.10.6 All spindle drive motors must be protected from overspeed by a feedback control system from each respective motor.

3.11 Work Light

Adequate lighting of three (3) wire grounded and shielded design shall be provided to illuminate the work area(s). The light(s) shall be permanently attached and wired to the machine with adjustable positioning capability. The design of the lighting system shall be subject to General Electric approval.

3.12 General Electric Company's Utilities

The vendor shall provide all transformers, converters, filters, adjusting valves, etc., which are required for the operation of the machine, in accordance with this specification, from the following customer utilities.

3.0 REQUIREMENTS (Cont'd.)

3.12.1 Electrical

Electrics to be 230/460-volt, 3-phase, 60-Hertz and all controls are to be stepped down to 115 volts at the push-buttons. (Note: All electrics are to be General Electric wherever economically possible).

3.12.2 Air

Shop air line pressure is available at 80 PSI at 25 CFM.

3.13 Travel Actuators

3.13.1 All longitudinal, transverse, and vertical travel motions shall be direct-driven by high torque, low speed d.c. motors through pre-loaded precision ball screws. Rotating motions will be driven by adjustable variable lead worms and precision worm wheels.

3.14 Fourth Axis (B-axis)

3.14.1 The fourth axis shall consist of an assembly of a four station rotary workpiece carrier, an electric servo-drive motor, a feedback positioning system, necessary anti-backlash gearing, and instrument gearing.

3.14.2 The workpiece carriers shall be capable of unlimited rotation.

3.14.3 The workpiece carrier stations centers shall be spaced a minimum 11" from each other.

3.14.4 The workpiece carrier stations shall be capable of holding all parts specified in Paragraph 3.1.5. A convenient and accurate means will be provided for installing and locating the work holding adapters. The workpiece carrier stations shall have a minimum angular resolution of not less than .001 degrees of arc. The distance from the A axis ℄ to the mating surface common to the B axis surface and the Impeller fixture shall be 3.937 inches (Reference G.E. drawing No.'s 4096785-757 and/or 4096785-578).

3.0 REQUIREMENTS (Cont'd.)

3.15 Fifth Axis (A-Axis)

3.15.1 The fifth axis will tilt the axis of rotation of the work-piece carriers vertically a minimum of -10 to 110° from their horizontal position.

3.15.2 The fifth axis shall consist of an assembly of a four-station rotary workpiece carrier, a tilting trunion, an electric servo-drive motor, a feedback positioning system, necessary anti-backlash gearing, an instrument gearing.

3.15.3 The fifth axis shall have a minimum angular resolution of not less than .001 degrees of arc.

3.15.4 Fifth axis lockout means shall be provided to mechanically hold and electrically disconnect this axis by N/C command and electrical pushbutton.

3.16 Ranges & Capacities

The following ranges and capacities are minimum requirements unless otherwise specified: (Supplier to provide specifications of proposed machine).

3.16.1 Table

Shall conform to accept G. E. fixtures - drawing numbers: 4096785-574, 4096785-575, 4096785-576, 4096785-577, 4096785-578

3.16.2 Range of Travel

| | |
|---|---|
| Longitudinal axis travel | 10.0000" minimum |
| Transverse cross slide travel | 17.0000" minimum |
| Vertical spindle travel | 8.0000" minimum |
| Workpiece rotation | 360° minimum |
| Workpiece tilting | 120° minimum |

3.0 REQUIREMENTS (Cont'd.)

3.16.3 Range of feed rates (All infinitely variable)

| | | | |
|---|---|---|---|
| Longitudinal | (X-axis) | 0-100"/minute | (Minimum) |
| Transverse | (Y-axis) | 0-100"/minute | (Minimum) |
| Vertical | (Z-axis) | 0- 60"/minute | (Minimum) |
| Rotational | (A&B axis) | 0-3.3 RPM | (Minimum) |
| Rapid Traverse | | 0-150 IPM | (Minimum) |

All axis shall be capable of moving simultaneously at maximum rate.

3.16.4 Spindle motor horsepower

Five (5) per spindle minimum available.

3.16.5 Distance between the centerlines of the machine spindles and the workpiece carrier with its axis in its vertical position shall be:

| | |
|---|---|
| Toward the column | 8.0000" Maximum |
| Toward the front | 10.0000" Maximum |

3.16.6 Distance between the machine spindle noses and the workpiece carrier face plate surface with its axis in its vertical position, with the spindle heads fully retracted, shall be:

| | |
|---|---|
| Spindles advanced | 3.0000" Maximum |
| Spindles retracted | 12.0000" Maximum |

3.16.7 Spindle speed range: 480-12,000 RPM

3.17 Machine Controls

3.17.1 The basic machine shall be provided with a numerical contouring control, manufactured by the Industrial Control Products Department of the General Electric Company, Waynesboro, Virginia and designated as the Mark Century 1050.

3.0 REQUIREMENTS (Cont'd.)

3.17.2 The Mark Century 1050 control will contain five (5) axes, capable of simultaneous positioning and contouring: three (3) linear axes and two additional rotary axes. This control will contain all of the standard basic features and be as described in General Electric Specification NEC1173B.

3.17.3 A separate moveable control panel, conveniently located at the front of the machine with controls consisting of but not limited to the following functions shall be provided: Emergency Stop, Cycle Start and Stop, Coolant On and Off, Air On and Off, Mist Collector On and Off, Work Light On and Off, A axis clamp On and Off, Machine Power On and Off, Feedhold, Z Retract Tool Change, Jog, Incremental Jog, % Feedrate, Feedrate and N/C Remote Selector.

3.17.4 Emergency stop shall immobilize servo motors X, Y, A & B immediately and provide for retraction of tool in Z axis for a minimum of 1/2" at rapid traverse prior to stopping all other machine functions.

3.17.5 Mark Century 1050 Control Requirements

3.17.5.1 Multiple Part Program Storage
One (1) Two (2) and Three (3) additional memory units to a total of Sixty (60) K.

3.17.5.2 Part Program Edit with modification files.

3.17.5.3 Programmable Subroutines (Macros).

3.17.5.4 300 CPS Tape Reader with 7 1/2" diameter reels and tumble box.

3.17.5.5 Programmable Interface

3.17.5.6 Machine diagnostics for programmable interface
Supplier to concur in application of this option.

3.17.5.7 Selectable Plane Cutter Radius Compensation
64 values (if not standard).

3.0 REQUIREMENTS (Cont'd.)

3.17.5.8 Separate N4 Sequence Number Readout

3.17.5.9 Sequence Number Search - Forward and Reverse

3.17.5.10 Additional 256 character Alpha-numeric Readout

3.17.5.11 Expandable Multiple Block Buffer Storage
To increase the standard eight (8) block buffer storage to one hundred twenty-eight (128) blocks of storage.

The basic machine is to be tested for alignment and accuracy at the supplier's facility, prior to acceptance and shipment in accordance with the supplier's own inspection standards. A copy of these standards will be submitted at the time of quotation for the customer's prior approval. Any or all of the tests may be witnessed by the customer's representatives. The supplier will provide the customer with a certified copy of the test results.

3.18 Machine Accuracies

The four (4) position work piece carrier (axis A and B) will be inspected to the following accuracies and alignments:

3.18.1 Index Accuracy (Axis A & B) $\pm$ 00° 00' 15" of arc.

3.18.2 Reverse Motion Loss (Axis A & B) $\pm$ 00° 00' 15" of arc.

3.18.3 Radial Runout of Work Piece Carrier 0004 inches T.I.R.

3.18.4 Axial Runout of Work Piece Carrier 0004 inches T.I.R.

3.18.5 Radial Runout of Toolholder Locating Surface
.0002 inches T.I.R.

3.18.6 Horizontal Alignment of Work Piece Carrier to Bedway Motion

.001"/ft.

3.0 REQUIREMENTS (Cont'd.)

3.18.7 Vertical Alignment of Work Piece Carrier to Bedway Motion

.001"/ft.

3.18.8 Distance of axial locating feature in spindles to face of work piece carriers

All spindles to all workpiece carriers to be the same within .001 inches T.I.R.

3.18.9 Stability of ℄ to ℄ (Spindle to Rotary Table) is required over the entire operating range of speeds and at 40 IPM resultant feed rate. Six (6) cylinders must be machined with a maximum ℄ shift of .001 inch allowable. A cylinder and plane must be machined in the following sequence at min. eight (8) hours frequency or one (1) hour after recording stable system temperature.

Machine must be in cold condition

Cut cylinder/plane #1

Run at 4000 RPM with all axis being exercised

Cut cylinder/plane #2

Run at 6000 RPM with all axis being exercised

Cut cylinder/plane #3

Run at 8000 RPM with all axis being exercised

Cut cylinder/plane #4

Run at 10,000 RPM with all axis being exercised

Cut cylinder/plane #5

Run at 12,000 RPM with an axis being exercised

3.0 REQUIREMENTS (Cont'd.)

3.18.9 Cut cylinder/plane #6

Measure and record TIR in .000X" of each cylinder. Cutter radius compensation may be used to obtain different radii for each cylinder.

3.18.10 Squareness of longitudinal slide with respect to the transverse slide shall be within .001"/ft.

3.18.11 Squareness of longitudinal slide with respect to the vertical slide shall be within .001"/ft.

3.18.12 Squareness of transverse slide with respect to the vertical slide shall be within .001"/ft.

4.0 ADDITIONAL REQUIREMENTS

The vendor shall quote a separate price for each of the following additional features: (unless standard with his equipment).

4.1 Machine Options

4.1.1 Off-Machine Tool Setting Device: Optical or mechanical tool setter to establish precise end length dimension and runout of cutting tools. To accept number 40 milling machine shank tool holders.

4.1.2 Adaptive Control: A sensing system to detect and monitor one (1) or more of the following conditions of the machining process as follows:

A. Cutter spindle deflection
B. Cutter deflection
C. Cutter temperature
D. Cutter vibration

System sensitivity must be capable of detecting a minimum cutting force of ten (10) pounds and a normal force of ten (10) pounds (approximately).

4.0 ADDITIONAL REQUIREMENTS (Cont'd.)

4.1.3 Tool Holders: To accept 1/4" - 3/16" - 5/16" diameter carbide end mills equivalent to the following G. E. drawing numbers:

1/4" diameter - GE # 4096785-901
3/16" diameter - GE # 4096785-801
5/16" diameter - GE # 4096785-800

4.1.4 Other: Supplier to indicate

5.0 OPERATING & INSTALLATION DOCUMENTS

5.1 As soon as the "design and engineering" of the equipment is completed the vendor shall provide to the General Electric Company:

5.1.1 A completed General Electric "Installation Data" Form #DF-10 certified by the vendor.

5.1.2 Three (3) certified copies of the scaled plan view, front elevation and end elevation drawings showing location and sizes of all required services, together with foundation, mounting, and interconnection details.

5.1.3 Design layouts, including wiring and piping diagrams for General Electric Company's review and approval.

5.2 At time of shipment, the vendor shall provide four (4) complete sets of:

5.2.1 Parts List and Maintenance Manual, including preventative maintenance and lubricating instructions.

5.2.2 Operating Instructions, including a complete programming manual and diagnosing test tapes.

5.2.3 Electrical, Mechanical, and Piping Diagrams.

5.2.4 Recommended Spare Parts List.

6.0 PROGRESS REPORTS

6.1 Within twenty-one (21) days after receipt of the General Electric Company order, vendor shall provide General Electric Company with a plan showing times and sequence of major events during the construction and testing of the equipment.

6.2 Fully explained progress reports will be supplied to General Electric Company every month until the order is 70% completed, after which these reports shall be submitted weekly until completion. In any event the vendor shall notify the General Electric Company of any change in the schedule as soon as it occurs.

7.0 EQUIPMENT ACCEPTANCE

7.1 The vendor shall demonstrate, in his plant, that the equipment complies with the accuracy and functional requirements of this specification, under the observation of General Electric Company representative(s). The test procedure shall include, but not be limited to the following:

7.1.1 A demonstration of all equipment and control functions and of the equipment accuracy per Section 3.0 of this specification. (The General Electric Company has the option of requiring any or all of the tests in the procedure, including the option of using his own inspection equipment and any additional test procedures deemed necessary).

7.1.2 Part Processing: One (1) application from the list of production parts identified in Paragraph 3.1.5 will be selected for processing at the vendor's plant. Part identification and quantity to be determined at a later date by mutual agreement.

7.1.2.1 The vendor will provide the machine tool, qualified operator(s) and commonly available shop tools and inspection devices.

7.1.2.2 The General Electric Company will provide the control tape(s), cutting tools, part holding fixtures and special inspection devices, as well as simulated or actual production parts.

7.0 EQUIPMENT ACCEPTANCE (Cont'd.)

7.1.2.3 The vendor's responsibility for the successful processing of these parts will be limited to the proper operation, accuracy and function of all resources supplied by him.

7.1.3 A minimum of one hundred (100) hours of machine operating time must be logged at the vendor's facility, prior to shipment. The operating conditions shall be representative of the entire range of the machines specified capabilities with no scheduled shutdowns.

7.1.4 Test block holders to be in accordance with or equivalent to General Electric drawing number SKDT41178. Tool block height setting dimension to be specified.

7.2 Authorization to ship will be based on the successful completion of the equipment demonstrations per paragraph 7.1.

7.3 Final acceptance will be made in General Electric Company's Hooksett Plant and will be based on a successful demonstration that the equipment fully meets the requirements of this specification.

7.4 The vendor shall supply a service engineer in the General Electric Company's plant at no additional charge for a time sufficient to start up the equipment, carry out the final acceptance, and train operating personnel.

7.5 The vendor shall submit to the General Electric Company two (2) certified copies of his machine test results prior to scheduled demonstration of these tests.

8.0 PAINT

Color required: Basic machine and control unit - to be specified on purchase order.

The basic machine and all associated components shall be painted with chemically resistant paint.

9.0 WARRANTY

Assuming the equipment is used under normal operating conditions, all repair service and required replacement parts shall be provided free of charge to General Electric Company by the vendor for a period of twelve (12) months from the date of final acceptance.

10.0 SHIPPING REQUIREMENTS

Upon acceptance for shipment, the seller shall ship the equipment FOB receiving dock, LPM, General Electric Company, Plant II, Daniel Webster Highway, Hooksett, New Hampshire 03106.

GENERAL ELECTRIC COMPANY
Aircraft Engine Group

Installation Data

Equipment Name:

Specification No: EE-183 ____ Rev: ________

Purchase Order No: ______________________ Machine Ser No. ____________

1. Shipping Weight: lbs. 1.a. Floor Space Req. ________

2. AC Electrical Motors

| | H.P. | Voltage | Amps | Phases |
|---|---|---|---|---|
| a. | | | | |
| b. | | | | |
| c. | | | | |
| d. | | | | |
| e. | | | | |

3. D.C. Motors

| H.P. | Volts | Converter Provided |
|---|---|---|
| | | |
| | | |
| | | |

4. Other Electrical Requirements ______________________________

5. Control Panel Mounting: Attached to Machine ☐ Separate ☐

*6. Special foundation required: YES ☐ NO ☐

*7. Machine requires lagging: YES ☐ NO ☐

8. Leveling Accuracy required ______________________________

9. Services Required:

| | | |
|---|---|---|
| air ____________ | pressure ________ | amount ____________ |
| steam ____________ | pressure ________ | amount ____________ |
| water ____________ | pressure ________ | amount ____________ |
| gas (natural) ______ | pressure ________ | amount ____________ |
| drain ____________ | clear water ______ | special (specify) ________ |
| electric ____________ | other ______________________ | |

Vendor: ______________________________ Date ____________

Signed ______________________________ Phone ____________

*If "Yes", vendor to include descriptive information.

| SUBJECT | STANDARD | DATE ISSUED / NO. |
|---|---|---|
| ELECTRIFICATION OF MACHINE TOOLS AND INDUSTRIAL EQUIPMENT | REPETITIVE DESIGN ELECTRICAL | 10/30/72 / S1231-06 |

STANDARD

## SECTION 1 - GENERAL

1.1 Scope

This Standard is to establish requirements for the design and construction of the electrical portions of machine tools and other equipment.

Section 2 details the provisions such as power supply, diagrams, type of disconnect, etc., as outlined in E1.9, "Additional User Requirements" of Joint Industrial Council Electrical Standards for General Purpose Machine Tools which are required to meet Purchaser's installation requirements.

Section 3 lists those modifications to the Joint Industrial Council Electrical Standards for General Purpose Machine Tools required by this Department of the General Electric Company.

(*) 1.2 Basic Standards

Electric components and methods shall be in accordance with the Occupational Safety and Health Standards of the Occupational Safety and Health Act, the National Electrical Code and current Joint Industrial Council Electrical Standards for General Purpose Machine Tools, EGP-1-1967, 2139 Wisconsin Ave., Washington, D.C., 20007, hereinafter referred to as OSHA, NEC and EGP respectively, except as modified in Sections 2 and 3, following. If exceptions are taken, they must be agreed to by the Purchaser's Engineer in writing. Quotations shall be for equipment conforming to these Standards, or shall state any variances therefrom.

NOTE: Although it is recognized that the EGP is a specification for the electrification of machine tools, the basic electrical requirements listed herein and in EGP shall be applied to welders, ovens, furnaces, presses and other special types of industrial equipment. When, therefore, the equipment being quoted is not a machine tool, it shall be the intent of this specification that any equipment quoted shall, unless otherwise agreed to in writing, comply with the requirements of this specification.

1.3 Electrical Equipment

a. Electric equipment as manufactured by General Electric Company shall be used.

b. Any exception to the above shall be agreed upon with the Purchaser's Engineer in writing prior to acceptance of quotation.

STANDARD

1.3 **Electrical Equipment (continued)**

c. Such exception shall be in addition to the approval of prints, and shall apply to the order in question only.

d. D-C equipment shall also conform to these specifications.

1.4 **Compliance**

Compliance with these specifications shall be indicated by reference to them on quotation and diagrams.

## SECTION 2 - Purchaser Requirements

2.1 **Power Supply**

2.1.1 The equipment builder shall supply the necessary transforming or converting means to operate supplied equipment from the available power supply. Nominal rating of the power supply is as follows:

AC: 480 volts, 3 phase, 3 wire, 60 cycles (grounded wye). In certain instances, when specified by the Purchaser, the power supply may be 240 volts, 3 phase, 3 wire, 60 cycles (ungrounded).

2.1.2 Motors shall be rated 230/460 volts, and shall be 3 phase wherever possible.

2.1.3 Control Power Transformers shall be 240 x 480 volts primary, and 120 volts secondary.

2.1.4 The machine tool shall be supplied set up for operation at the voltage specified by the Purchaser.

2.2 **Direct Current**

2.2.1 Direct current is not available at the Purchaser's plant. Where D-C is required, the equipment builder shall supply packaged conversion units. The Purchaser's preference is toward static conversion or brushless rotating equipment.

2.3 **Short-Circuit Protection**

2.3.1 The Purchaser's typical 1000 KVA 480 V substation has a short-circuit current availability of 25,000 amperes, asymmetrical. When loads require larger power sources, the purchaser should be consulted for the available short circuit rating.

2.3 Short-Circuit Protection (continued)

2.3.2 For the proper short circuit protection of electrical equipment, the fuses shall be dual element type with a short circuit current interrupting capability of 100,000 amperes RMS such as provided by Chase-Shawmut "Trionics" or an approved equal.

2.4 Portable Equipment and Trolley Applications

2.4.1 Equipment employing plugs and receptacles, reels, trolleys, etc., shall be referred to the Purchaser's Engineer for his special requirements. See Para 3.6.1 and Para. 3.6.2

2.4.2 If equipment is to use trolleys, enclosed bus is required. A separate grounding conductor shall be used in the trolley configuration.

2.5 Preliminary Data Required by Purchaser

2.5.1 At the time the machine is quoted, equipment builder shall furnish to the purchasing representative for evaluation by the Department's Electrical Engineer for approval, two (2) sets of electrical proposition specifications, as submitted to him by the electrical equipment supplier.

2.5.2 Three (3) sets of final approved reproducibles shall be forwarded to the Electrical Engineer not later than one week prior to the date on which the machine tool is to be shipped.

2.5.3 On machines requiring foundation work, Purchaser will advise when foundation plans will be needed.

2.5.4 Foundation prints shall show routing and sizes of all conduits and junction boxes with each identified. This same identification shall be used on the interconnection diagram.

2.5.5 Interconnection diagram shall show all wires to be run in each conduit; the number, size, color and type of each wire in each conduit.

2.5.6 Prints supplied should be completely coordinated.

2.6 Supply Circuit Disconnecting Means (EGP Section E3)

2.6.1 Up to and including 200 amp nameplate rating, the disconnecting device shall be a heavy-duty fusible switch, or a non-automatic circuit breaker with fuses on its load side.

2.6 Supply Circuit Disconnecting Means (EGP Section E3) continued

2.6.2 Above 200 amps nameplate rating, the disconnecting device shall be a properly rated type AK air circuit breaker with overcurrent and instantaneous trips in each pole. Breaker shall be manually operated unless electrical operation is required for the control. Refer to the Purchaser's Engineer for the trip characteristics.

2.6.3 Molded case circuit breakers shall not be used as disconnecting means without permission in writing from the Purchaser's Engineer.

2.6.4 A single disconnecting device shall be provided to open all power sources to the machine simultaneously.

2.6.5 See GE Standard 1251-30 for special provisions applying to resistance welders.

2.7 Motors (EGP Section E14)

2.7.1 A-C motors shall be totally enclosed, fan-cooled.

2.7.2 D-C motors shall be totally enclosed, except blower ventilated motors, with filters, may be used if required by the application.

2.7.3 Machines whose total motor load exceeds 100 hp shall be considered a special installation and shall be referred to the Purchaser prior to submission of quotation for evaluation of the type of starting equipment required.

2.8 Pre-Wired Equipment

2.8.1 When machines are wired at the builder's factory and then disassembled for shipment, conduits and wires shall be plainly marked for ease in final assembly.

2.9 Safety

2.9.1 On machines where an operator might be caught between work and cutter, a means for emergency stopping must be provided independent of the normal stopping means.

2.10 Electronic Equipment

2.10.1 When major electronic or numerical controls are required on a machine GE Standard 1231-07 shall also apply.

2.10.2 This addendum would not be required when the electronics involved consist only of electronic motor starters, electronic exciters, electronic regulators, etc.

2.11 Wiring for Hazardous Locations

2.11.1 Any equipment that is ordered for installation in a hazardous location shall be referred to the Purchaser's Engineer for design considerations. In many instances, controls, etc., can be mounted outside the hazardous area, thereby minimizing the quantity of special wiring.

2.11.2 Any dip tank, cleaning equipment or other types of equipment that will contain any liquid whose open cup flash point is 200°F or lower will, in itself, classify that piece of equipment as a hazardous location and all electrical materials located thereon must conform to NEC requirements for hazardous locations. As in the preceding paragraph, equipment that falls within this category shall be referred to the Purchaser's Engineer.

2.11.3 Any equipment that is supplied prewired for hazardous locations shall be in strict compliance with the NEC requirements for hazardous locations.

2.12 Associated Jib Hoists and Other Hoisting Apparatus

2.12.1 Jib hoists, monorails, cranes, etc., furnished as a part of a machine tool package, shall conform to these Standards, and further, shall also conform to GE Standards 1251-12, 1251-13 and 1251-15.

SECTION 3 - Modifications or Additions TO EGP

3.1 Diagrams (EGP Section E2)

3.1.1 In paragraphs E2.4.1 and E2.8, appropriate information shall be furnished (not should be furnished).

3.1.2 The layout drawing (EGP Section E2.8) shall show the location of all electrical components on the machine, except for single-motor machines.

3.1.3 A sequence of Operations shall be included on the Elementary Diagram (EGP Para E2.6).

3.2 Control Circuits (EGP Section E5)

3.2.1 Paragraph E5.2 Exception No. 3 is changed to specify that devices exceeding 20 amperes inrush at 120 volts shall be energized through relay contacts.

3.3 Control Components (EGP Section E6)

3.3.1 Preference shall be given to the use of vane-type or proximity limit switches wherever practicable.

3.3.2 Air circuit breakers, including molded cast types, shall not be used as motor starters, or as contactors.

3.4 Control Enclosures (EGP Section E7)

3.4.1 Custom built panels shall include 15% clear mounting space for the ultimate user to add control components, and as a minimum, this space shall be sufficiently sized to accommodate three (3) NEMA size 1 Contactors.

3.4.2 Nothing shall be located in the bottom of any enclosures which shall interfere with bringing in conduits.

3.4.3 Enclosure doors shall have provision for locking.

3.5 Location and Mounting (EGP Section E8)

3.5.1 Machine mounted enclosures shall be used whereever practicable and shall be so located that external operating handles will be readily accessible to the operator.

3.5.2 Devices requiring frequent mechanical adjustment by an operator shall be adjustable without opening the enclosure door.

3.6 Electrical Accessories (EGP Section E10)

3.6.1 Plugs and receptacles, if used for connection of machine to power source, shall be selected from those listed in the Purchaser's Standard No. 1251-02, copies of which will be furnished on request.

3.6.2 Plugs and receptacles, if used for machine component interconnection, shall be selected so as to be incompatible with those listed in Purchaser's Standard No. 1251-02, copies of which will be furnished on request. A list of plug and receptacles proposed for this application shall be submitted to the Purchaser's Engineer for approval.

3.6.3 If control panel and machine work lights are supplied from the 120 volt machine tool control circuit, a seperate overcurrent protective device shall be provided. These lights shall be wired direct, without plugs and receptacles.

3.7 Conductors (EGP Section E11)

3.7.1 Specific conformance to minimum conductor size and stranding requirements as described in EGP Para E11.1 is required.

3.7.2 Conductors shall be stranded.

3.7.3 Conductors supplying work lights (EGP Para E10.2.4) may be type STO or SJO.

3.8 Wiring Methods and Practices (EGP Section E12)

3.8.1 (EGP Para E12.3.4) Plugs and receptacles shall be used only for connections to power source and to separable parts of the machine tool, and only with the approval of the Purchaser's Engineer. See para 3.7 and EGP para E12.4.11.

3.8.2 Circuits from more than one source shall not be run in the same conduits unless all sources can be simultaneously disconnected when work is to be done on any circuit.

3.8.3 Signal circuits subject to interference shall be effectively shielded where necessary, and run in separate metallic conduits, if possible.

3.9 Raceways, Fittings and Boxes (EGP Section 13)

3.9.1 All raceways and cables shall be U.L. approved and shall be properly supported and protected.

3.9.2 The attention of the machine tool builder is particularly directed to EGP Section 12.4 regarding the use and installation of flexible wiring and raceways.

3.10 Motors (EGP Section E14)

3.10.1 D-C motors which cannot safety withstand a speed increase to above their rated speed shall be provided with a mechanical overspeed switch. The operation of this switch shall cause power to be removed from the armature of the motor.

3.10.2 Wherever shunt-would or compount-wound D-C motors are used, field-loss relays shall be provided.

3.10.3 D-C motors capable of overspeed shall not be belt-connected to their loads, whether or not supplied with overspeed switches and/or field-loss relays.

3.10 Motors (EGP Section E14) continued

3.10.4 All motor-driven couplings, belts and chains shall be easily replaceable.

3.11 Grounding (EGP Section E15)

3.11.1 Equipment grounding shall also conform to the Purchase's Standard No. 1251-01, which shall take precedence over EGP Section E15 in cases of conflict.

3.11.2 One side of the control circuit shall be grounded by the machine builder. 1

3.11.3 A green insulated equipment grounding conductor shall be run to all motor terminal boxes and to all fixed and pendant control stations.

(*) THIS STANDARD DOES NOT CONFLICT WITH OSHA REQUIREMENTS AS OF MAY 31, 1972.

(*) INDICATES AREAS OF REVISION FROM PREVIOUS ISSUE.

# GENERAL ELECTRIC

AIRCRAFT ENGINE GROUP

# PLANT ENGINEERING & CONSTRUCTION STANDARDS

| SUBJECT | STANDARD | DATE ISSUED / NO |
|---|---|---|
| ELECTRONIC STANDARDS FOR INDUSTRIAL EQUIPMENT | REPETITIVE DESIGN ELECTRICAL | 6/1/73 |
| | | S1231-07 |

1. SCOPE:

1.1 The purpose of this Electronic Standard is to provide detailed specifications for the construction and application of electronic apparatus to industrial equipment which will promote:-

- 1.1.1 Safety to personnel
- 1.1.2 Uninterrupted production
- 1.1.3 Long life of equipment
- 1.1.4 Ease and low cost of maintenance

1.2 This Standard is not intended to limit or inhibit advancement in the applied science of electronic, electrical or mechanical engineering.

1.3 Exceptions and deviations by the Manufacturer with respect to any portion of this Standard shall require the Purchaser's written agreement and shall be considered only if the Manufacturer defines such exceptions and deviations in writing prior to confirming the purchase order and shall apply only to the order in question.

1.4 Compliance with these specifications shall be indicated by reference to them on quotations and diagrams.

2. APPLICABLE INDUSTRY STANDARDS

2.1 Electronic Industries Association (EIA) Standard RS-281, "Construction Standards, Numerical Machine Tool Control" shall apply to all electronic equipments, panels, apparatus and chassis.

2.2 G.E. Standard 1231-06 "Repetitive Design Electrical". *

*"Specification for Electrification of Machine Tools and Industrial Equipment".

2.3 Joint Industry Council (JIC) Standard EGP-1-1967; "Electrical Standards for General Purpose Machine Tools" shall apply to all equipments which have electronic and electrical apparatus applied together.

2.4 American National Standards Institute (ANSI) Standard Y32.2-1967; "Graphic Symbols for Electrical and Electronics Diagrams" shall apply to all electronic equipment prints, reproducible and diagrams.

| ISSUED BY MANAGER OF PLANT ENGINEERING & CONSTRUCTION | SUPERSEDES | DATED | DISTRIBUTION | PAGE 1 OF 4 PAGES |
|---|---|---|---|---|
| | 1231-07 | 4/1/63 | | |

3. DRAWINGS AND INSTRUCTIONS:

3.1 Preliminary data to be furnished with quote. The builder shall submit, for Purchaser's approval, preliminary data on:

3.1.1 Schematic or Elementary diagrams

3.1.2 Electronic equipment layout

3.1.3 Stock or Material List

3.1.4 Theory or sequence of operation

3.1.5 Information on recommended test instrumentation or other special equipment for use on supplied equipment. If instrumentation is not available commercially, it should be made available by supplier.

3.2 Final data requirements

3.2.1 One complete set of elementary diagrams, of electronic control systems, shall be furnished in reproducible form.

3.2.2 Block diagrams of control functions shall be furnished, where applicable, in reproducible form.

3.2.3 Connection and Interconnection diagrams and/or tables shall be furnished in reproducible form.

3.2.4 Component and Equipment Location or Layout diagrams shall be furnished in reproducible form.

3.2.5 Three sets of instruction books including, where applicable:

3.2.5.1 Operating instructions including theory of operation.

3.2.5.2 Maintenance instructions including preventive maintenance, trouble-shooting guides and set-up and adjustment procedures.

3.2.5.3 Stock or Material List including a recommended spare parts list with original equipment Manufacturer's Catalog Numbers and Generic Descriptions.

3.2.6 A complete list of all print numbers with titles pertaining to the equipment supplied.

3.2.7 A complete set of test, check-out, and/or performance data including response curves, alignment data, and other similar data, where applicable.

3.2.8 Information on special schools and/or instructive material available on supplied equipments.

3.2.9 Information listing voltages, phase, frequency and volt-ampere requirements on supplied equipment. Nameplates shall be of a durable material, such as bakelite or metal.

3.3 Schematic or Elementary Diagrams. In addition to those items listed in the Reference Standards listed under Sec. 2, the following is required:

3.3.2 All internal and external connections to the pins for each plug-in device shall be shown giving adequate information on both male and female receptacles to facilitate the location of each connection promptly and correctly.

4. <u>COMPONENTS</u>:

4.1 It is recommended that plug-in devices be used wherever possible.

4.2 Tube and other component selection should be made from Manufacturer's preferred lists.

4.3 If special, matched, or limited characteristic components are used, such information shall be indicated on the schematic diagrams, stock list, and, if practical, on the equipment chassis or nameplate.

5. <u>CONSTRUCTION PRACTICE</u>

5.1 Mechanical.

5.1.1 It is recommended that equipment enclosures be constructed to give accessibility to contained components from the front.

5.1.2 All edges and corners on metal assemblies shall be smooth and rounded.

5.1.3 Captive retaining clamps, screws, and devices shall be used wherever possible.

5.1.4 Resilient washers shall be used whenever plastic, phenolic, porcelain, or other brittle materials must be bolted in assembly.

5.1.5 Control knobs shall be fastened by two set screws or other positive method.

5.2 Electrical.

5.1.1 Required connections from cable shield to both connector pin and cable clamp shall be made from the shield directly to the pin and the pin shall be connected to the cable clamp by hook-up wire. Connection to the clamp shall be made by lug.

5.1.2 Whenever a cable is terminated in a connector, an appropriate cable clamp shall be used to secure the cable.

5.1.3 The connector cable clamp of the appropriate size shall be mounted around the outer insulation covering of the cable.

5.1.4 Connections and clamps shall be sufficiently tight to prevent damage to connections during assembly and use.

5.1.5 Oil tight construction shall be used.

5.1.6 The energized portion of a circuit shall be connected to the female portion of interconnecting devices.

5.1.7 All wires and cables shall be secured and protected to prevent strain on the wire termination or freying of the insulation.

5.1.8 Appropriate warning labels or tags shall be provided on enclosures shielding dangerous high voltages, sources of radiation, or both.

THIS STANDARD DOES NOT CONFLICT WITH OSHA REQUIREMENTS AS OF 9/22/72.

GENERAL ELECTRIC

AIRCRAFT ENGINE GROUP

# PLANT ENGINEERING & CONSTRUCTION STANDARDS

| SUBJECT | STANDARD | DATE ISSUED / NO. |
|---|---|---|
| ELECTRICAL GROUNDING | CONSTRUCTION & INSTALLATION ELECTRICAL | 5/22/75 |
| | | S1251-01 |

STANDARD

## SCOPE

This Standard will be used to supplement the grounding requirements of the NEC and covers the minimum provisions for the electrical grounding of all industrial equipment, lighting fixtures, and low voltage distribution equipment, and shall apply to all electrical work performed in the River Works unless otherwise specified in writing.

## EQUIPMENT GROUNDING

1- The grounding conductor shall in no case be a system neutral or a current carrying conductor. (In most cases the system neutral will be grounded. If this is the case, it must be grounded at only one location--at the transformer).

2- The enclosing cases, mounting frames, etc., of all switches, circuit breakers, control panels and other electrical equipment or electrically operated equipment must be grounded by running a grounding conductor from a ground established at the source of supply, to the equipment to be grounded.

3- This grounding conductor must be run inside the conduit or wiring channel enclosing the power conductors supplying the equipment, or in the case of a multi-conductor cable, must be located inside the sheath of the cable. The only exception to this is in the case of lead-sheathed power cable where the lead sheath may, in most cases, be used as a grounding conductor and must be connected to ground at each end.

4- All metallic conduits, wiring channels and the armor of armored cable or BX must be connected at each end to the grounding conductor or firmly attached at each end, with good electrical contact, to a properly grounded connection box. All connection boxes must be connected to the grounding conductor which must run through the box.

5- Where circuits consist of two or more power conductors in a conduit or wiring channel, the grounding conductor may be no more than one standard wire size smaller than the power conductor, but in no case smaller than #14, nor larger than #4/0. The grounding conductor shall be stranded and covered with a green Flameol (type T.W.) jacket up to #2AWG. Larger sizes may be bare stranded. If green is not available, the grounding conductor should be clearly and permanently identified at all terminating points or taps by the use of green marking tape, code markers or similar permanent identifying means.

In all cases the white wire should be used for the current-carrying neutral only and never as a grounding conductor.

6- In non-metallic multiconductor cables, the green conductor is to be used as the grounding conductor.

STANDARD

EQUIPMENT GROUNDING (Cont.)

7- In V.C. Interlocked Armor Cable, use the two or three grounding conductors which are placed between voids of the larger current carrying power and neutral conductors. Due to corrosive action causing increased resistance with age, the sheath of the interlocked armor cable does not make a satisfactory ground. The combined sizes of the grounding conductors furnished with interlocked armor cable equals about 50% the size of one power conductor.

(*) 8- Where BX cable is specified in AWG sizes 12 and 14, increase the number of conductors in the cable by one, and use the red insulated conductor (same size as the power conductor) as the ground wire. The ground wire in non-metallic sheathed cable is of adequate size.

9- If the structures or devices covered by paragraph 2 are so located as to be within six feet of a metallic ground such as building steel, metal pipes or troughs, or other machine frames -- and also are not interconnected mechanically by structural beams, pipes, conduits, or the like, whose circuit length is 100 feet or less -- they should be directly interconnected by a bare copper cable of the size indicated in paragraph 5, except in no case smaller than #6 AWG.

(*) 10- BUSWAY:

Where metal enclosed plug-in busway is used, the busway should be provided with an internal grounding bus, and the plug or trolley devices provided with contact stabs or trolleys for making contact with this grounding bus. This grounding bus should be positively connected to the grounding conductor at the point of supply and should make good electrical contact with the bus enclosure at least at both ends of the bus run.

In those types of busway where an internal grounding bus is not available or not specified (this should be avoided if possible), the busway enclosure may serve as the continuation of the equipment ground, provided the following requirements are satisfied.

a- Installation of bus - When installing the busway system, insure tight, electrical connecting joints between adjacent sections of busway housing. The ground wire of the feed cable to the bus must be solidly connected to the feed-in box enclosure, which in turn must be solidly connected to the busway enclosure.

b- Plug connection - When inserting the plug-in device, the attaching clamps or other holding devices must be tightened, particularly on painted surfaces, to insure good electrical contact between bus and plug housings. The grounding conductor in the cable drop from the plug-in device to the equipment shall be connected to the plug housing by a ground lug.

11- GROUNDING OF LIGHTING FIXTURES:

a- All lighting fixtures, whether incandescent, mercury or fluorescent, must be

11- GROUNDING OF LIGHTING FIXTURES (Cont'd) .....

grounded in accordance with the above. Where fluorescent fixtures are mounted in continuous rows, each fixture unit must be individually grounded.

12- TRANSFORMER GROUNDING:

a- All standard 1000 KVA, 13.8 KV, 480Y/277 volt A.C. substations have the transformer neutral grounded at the substation. This neutral shall not be grounded at any other location. The transformer enclosure is also grounded.

b- Single phase systems in the low voltage range, supplied from a single phase transformer must be grounded at the transformer. Where a mid-tap is available (as with the Edison system), the ground should be at this mid-tap.

13- WELDING

In order to prevent damage to the equipment grounding conductors of arc welding transformers or motor generator sets, such equipment must never be operated without a return conductor from the work, of sufficient capacity to carry the welding current.

14- BURIED GROUND CONNECTIONS:

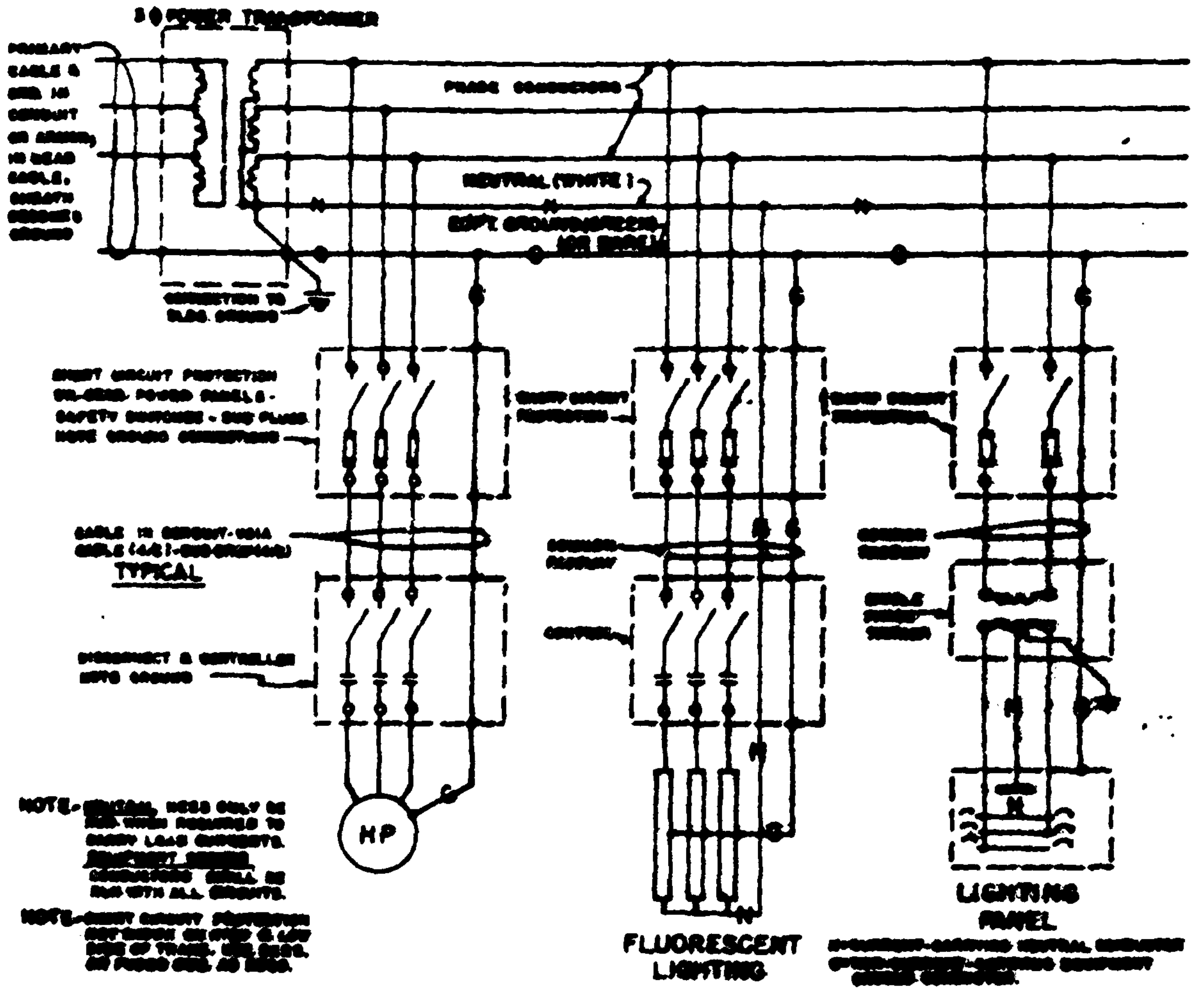
All buried ground connections shall be made by brazing or Thermit welding, similar to the Cadweld process. All other ground connections shall be made by brazing, welding, or with approved pressure terminals properly applied.

15- OPEN WIRE FEEDERS

When making a branch connection to an open wire feeder, the branch circuit equipment ground wire will connect onto a continuous ground conductor run parallel to the open wire feeder, or if this parallel ground conductor is not available, the ground connection will be made into building steel in close proximity to the splice point.

(*) THIS STANDARD DOES NOT CONFLICT WITH ANY SECTION OF NEC OR OSHA AS OF OCTOBER 1, 1974 AS AMENDED.

(*) INDICATES AREA OF REVISION FROM PREVIOUS ISSUE.


TYPICAL
HP
FLUORESCENT LIGHTING
LIGHTING PANEL

GENERAL ELECTRIC

AIRCRAFT ENGINE GROUP

# PLANT ENGINEERING & CONSTRUCTION STANDARDS

| SUBJECT | STANDARD | DATE ISSUED / NO. |
|---|---|---|
| WIRE AND CABLE COLOR CODING | CONSTRUCTION & INSTALLATION ELECTRICAL | 11/20/72<br>NO. S1251-20 |

STANDARD

## SCOPE

The purpose of this Standard is to establish a plan for the identification of conductors of the various electrical branch circuits, 0-600 Volts, as required by Article 210-5 of the National Electrical Code - 1971, and OSHA.

### COLOR CODE REQUIREMENTS

Electrical Distribution Systems
0 - 600 Volts

| | CONDUCTOR DESIGNATION [2] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System Description | A | B | C | Neut. | Grd [1] | 1 | 2 | Minus (-) | Plus (+) |
| 480Y/277 volts 3ø - 4W - 60 Hz | Black | Red | Blue | White Red Tracer | Green | | | | |
| 208Y/120 Volts 3ø - 4W - 60 Hz | Yellow | Brown | Orange | White Blue Tracer | Green | | | | |
| 120/240 Volts 1ø - 3W - 60 Hz | | | | White | Green | Black Yellow Tracer | Red Orange Tracer | | |
| 125/250 Volts 3W - DC | | | | Gray | Green | | | BL/W | BL/BK |
| Control AC | Red | | | | | | | | |
| Control DC | Blue | | | | | | | | |

1- Identifying strip of colored tape is an acceptable substitute for colored coded wire. The strip is to consist of two (2) 1/2" wide bands of tape separated by 1/2" space. The tape identifying solid color to be at least a 2" wide band.

2- Color coding is required at each junction in system.

**THIS STANDARD DOES NOT CONFLICT WITH OSHA REQUIREMENTS AS OF SEPTEMBER 22, 1972.**

STANDARD

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| PLANT ENGINEERING & CONSTRUCTION | S1251-20 | 4/5/62 | | 1 PAGES |

# APPENDIX B

## SPECIFICATION FOR PRODUCTION ABRASIVE FLOW MACHINE

GENERAL ELECTRIC

AIRCRAFT ENGINE GROUP

Lynn
Engine
Manufacturing
Operation

Specification No. EE 81
Page 1 of 12
Date 9/14/76

Description: Abrasive Flow Facility

Prepared by:

R. Kuhn, Engineer
2-68 Ext. 4141

Proposed Facility Location
Lynn - Building: ____ Area ____
Satellite Plant: Hooksett, N.H.
Plant II
General Electric ____
Government X

Approved by:

R.L. Yeaton, Manager
T700 Blisks/Impeller PDP
Mail Drop 37426
(617) 594-2693

GENERAL ELECTRIC COMPANY

AIRCRAFT ENGINE GROUP

1000 WESTERN AVE. - LYNN - MASSACHUSETTS 01910

SE 1316-R

1.0 GENERAL:

1.1 Scope:

This specification will cover the requirements for a T700 Blisk/Impeller abrasive flow facility.

1.2 Instructions for Quoting:

1.2.1 The vendor shall quote his standard equipment and related accessories.

1.2.2 If vendor's standard equipment does not conform to any of the requirements listed here, he shall:

1.2.2.1 Quote his standard equipment and accessories.

1.2.2.2 Indicate how the standard machine does not conform,

1.2.2.3 Quote additional price of modifying the standard equipment to comply with this specification. Also state percentages of the additional price which are applicable to Engineering, Materials, & Mfg..

1.2.3 The vendor's quotation must state compliance with this specification. Some exceptions to this specification may be approved by the customer, therefore, exceptions must be detailed in the vendor's quotation with reference to the paragraph involved.

1.2.4 The vendor shall submit with his quotation, a completed General Electric "Data Form #DF-10" which will be considered preliminary until resubmitted in accordance with Para. 5.1.1.

1.2.5 The vendor's quotation shall include delivery time of entire equipment package and shall be based on arrival at the designated General Electric Company Plant.

1.3 Responsibilities of the Vendor:

1.3.1 The successful vendor shall be responsible for ensuring that the equipment supplied to the customer fully complies with the requirements of this specification including any deviations accepted by the General Electric Company as referenced in paragraph 1.2.3.

1.3.2 The equipment described herein shall be built to customer approved drawings. Customer approval of any document describing a design, process, or procedure does not waive or supersede any of the requirements of this specification nor the vendor's responsibility for fulfilling all of the specification requirements.

2.0 **APPLICABLE DOCUMENTS:**

The following documents shall form a part of this specification. Any exceptions shall be stated in the vendor's quotation. In cases where General Electric and other codes conflict, General Electric requirements shall apply.

2.1 General Electric Specification for the Electrification of Machine Tools and Industrial Equipment No. S1231-06, dated 10/30/72 . When the purchase order references a Government Contract number, the requirements for exclusive use of General Electric components, is waived.

2.2 General Electric Specification for Electronic Industrial Equipment No. S1231-07, dated 3/1/71.

2.3 General Electric Specification S1251-01, dated 12/13/68. (Electrical Grounding)

2.4 General Electric Specification S1251-20, dated 11/28/72. (Color Coding)

2.5 General Electric "Installation Data" form No. DF-10, dated

2.6 National Electric Code NFPA #70 (Latest edition)

2.7 The latest revision of the Joint Industrial Council's Electrical Standards for General Purpose Machine Tools.

2.8 The latest revision of the Joint Industrial Council's Hydraulic Standards.

2.9 National Machine Tool Builders Association (NMTBA) Standard

2.10 The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section VIII.

2.11 Applicable portions of the latest edition of the U. S. Department of Labor (Safety & Health Standards")- Commonly known as (O.S.H.A.)

GENERAL ELECTRIC
AIRCRAFT ENGINE GROUP

Lynn Engine Manufacturing Operation

Specification No. EE 81

Date 9/14/76

3.0 Requirements

## 3.1 FACILITY DESCRIPTION

### 3.1.1 General

The vendor shall supply an automatic abrasive flow machining facility including abrasive flow machinery, media, tooling and media removal equipment.

### 3.1.2 Media Cooling and Replenishment

The abrasive flow facility shall include the following features

An abrasive media cooling system designed to insure proper cooling of the media under continuous operation, and also to maintain uniformity of time for an operating cycle. The cooling system shall maintain the media at a temperature of 125°F or less during continuous operation.

An automatic media replenishing system which shall maintain the constant volume of media in the working system. The media tank for this make-up system shall be designed so that it shall require no tools to add compound.

### 3.1.3 Hydraulic System

The hydraulic fluid reservoir shall have a thermostat controlled cooling system which shall easily maintain the hydraulic fluid at least 10°F under its recommended maximum temperature during continuous operation.

### 3.1.4 Controls

A central control panel shall be provided and mounted in a convenient position for the operator to use in running the abrasive flow machine. This panel shall be equipped with all of the necessary controls, properly identified, for the safe operation of the machine.

The machine controls shall permit operation in either the automatic or semi-automatic mode.

The control panel shall include (but shall not necessarily be limited to) flow controls for the top and bottom media cylinders, media temperature indicating gage, media cycle counter, hydraulic pump pressure gage, clamping pressure gage, and all necessary start/stop buttons, selector switches, and indicating lights required for manual and automatic operational modes.

The machine start button shall be the dual and separated type requiring the use of both hands by the operator to hold the button depressed until the clamp close pressure has been applied.

The facility shall have the necessary safety devices to insure safe operation. These devices shall include (but are not necessarily limited to) guards, where required; work platform railings, if required, and electrical interlocks to insure operator safety and protection of the production part.

Controls shall be provided which allow abrasive flow machining a part only when machine settings have been made that provide proper parameters for that part.

3.1.5 Tooling

The abrasive flow machine shall have a dual production part holding fixture mounted on a two-station transfer unit which shall allow an operator to unload and reload a production part while loaded part holding fixture is in the process position.

The indexing of a part holding fixture into the process position shall be interlocked to prevent subsequent processing operations being initiated if the fixture does not index into the correct position of alignment between the upper and lower media cylinders.

The load/unload station shall be at the front of the machine.

The part tooling shall be designed of wear resistant material which shall insure long life and be easily maintained, and this design shall also have specific features to protect the production part. All tooling drawings shall conform to the Purchaser's "Tool Design Practices".

All tooling drawings shall be submitted for review prior to fabrication.

3.1.6 Cleaning Equipment

The facility shall include a cleaning station for removing all retained media from the part. This station shall consist of a mechanical and cycle timed air blow-off facility having all of the necessary safety interlocks, and an ultrasonic degreasing facility.

Acceptance of Machine
The vendor will demonstrate the capability of his proposed equipment to meet the customer's requirements by the successful processing of two each of the following components. The tests will be conducted at the vendor's plant with responsible GE personnel present.

Stg. 1 Blisk - GE drawing 6032T26
Impeller - 6035T18

## FACILITY FUNCTIONAL REQUIREMENTS

The facility will be capable of producing the final surface texture on the parts listed below, and will also be capable of removing all abrasive flow media from parts after abrasive flow machining. It shall meet the following requirements:

3.1 Parts
The parts involved are shown on GE drawing numbers 6032T26, 6032T27, 6035T23, 6035T47 and 6035T18

3.2 Surface Texture
Produce surface roughness on all airflow surfaces of 32 micro inches AA or better, starting with surface roughness of [illegible] micro inches AA as produced by contour milling.

3.3 Depth of Material Removed
Remove sufficient material to obtain required surface roughness. Depth removed may be different for different drawing number parts.

Depth of material removed from a given drawing number part must be the same over all airflow surfaces on all parts of that drawing number within the following limits:

o Blisk and impeller blade convex and concave surfaces, and platform surfaces - depth of material removed must not vary more than .0005 from max to min.

Blisk blade edges - depth of material removed at the leading and the trailing edges may be greater than the maximum removed from other surfaces, but not more than .003 in. greater.

Impeller blade leading edges - depth of material removed may be greater than the maximum removed from other surfaces, but not more than .0015 in. greater.

3.3.4 Surfaces Not to be Abrasive Flow Machined
Blisk blade tips, impeller blade tips, and impeller trailing edges will not be abrasive flow machined.

3.3.5 Removal of Media
Remove all media from part surfaces by using air to blow off essentially all media, followed by ultrasonic degreasing to remove all traces of media.

3.3.6 Production Capacity
The facility shall be capable of processing 20 sets of parts as listed above (a total of 100 parts) in 60 hours. This processing time is the abrasive flow machining floor to floor time which consists of part loading, unloading, machine control setting and operation, abrasive flow cycle time, media change time (if any), and media replenishment time.

3.3.7 Processing Time
The vendor shall quote the floor to floor abrasive flow machining time for each part and shall also quote the cleaning time for each part separately.

3.3.8 Parameters
The equipment tooling and process shall be capable of meeting the functional requirements on any quantity of each of the parts with preset machining parameters, such as media pressure and temperature and number of flow cycles. Different parameters may be used with different drawing number parts.

4.0 ADDITIONAL REQUIREMENTS:

The vendor shall quote a separate price for each of the following additional features:

GENERAL ELECTRIC
AIRCRAFT ENGINE GROUP

Lynn Engine Manufacturing Operation



5.0 OPERATING AND INSTALLATION DOCUMENTS:

5.1 As soon as the design and engineering of the equipment is completed, the vendor shall provide the customer:

5.1.1 A completed General Electric "Installation Data" form GDF-10, dated ( 3/24/69 ) and certified by the vendor.

5.1.2 Three (3) certified copies of the scaled plan view, front elevation and end elevation drawings showing location and sizes of all required services together with foundation, mounting, and interconnection details.

5.1.3 Design layouts, including wiring and piping diagrams for customer review and approval.

5.2 At time of shipment, the vendor shall provide one (1) complete set of reproducible electrical and piping diagrams to JIC standards.

5.3 At least ( 3 ) weeks before delivery of the equipment, the vendor shall provide:

5.3.1 Three (3) copies of the maintenance manual and parts list and the recommended spare parts list, including preventative maintenance and lubrication instructions.

5.3.2 Four (4) copies of the operating instructions.

5.3.3 Two (2) copies of the electrical, mechanical and piping diagrams.

6.0 PROGRESS REPORTS:

6.1 Within 30 days from receipt of General Electric order, vendor shall provide General Electric Company with a plan showing times and sequence of major events during the construction and testing of the equipment.

6.2 Fully explained progress reports will be supplied to General Electric Company every month until the order is 70% completed. After which, these reports shall be submitted weekly until completion. In any event, the vendor shall notify the customer of any change in the schedule as soon as it occurs.

7.0 EQUIPMENT ACCEPTANCE:

7.1 The vendor shall demonstrate, in his plant, that the equipment complies with the accuracy and functional requirements of this specification, under the observation of General Electric Company representative(s).

7.1.2 The test procedure shall include, but not be limited to the following:

7.1.2.1 A demonstration of all equipment and control functions, and of the equipment accuracy per Section 3.0 of this specification. (The customer has the option of requiring any or all of the tests in the procedure including the option of using his own inspection equipment.)

7.1.2.3 The successful processing of (          ) production parts as specified in Section 3.0.

7.2 Authorization to ship will be based on the successful completion of the equipment demonstrations per paragraph 7.1.

7.3 Final acceptance will be made in the customer's plant and will be based on a successful demonstration that the equipment fully meets the requirements of this specification in accordance with paragraph 7.1.2.

7.4 The vendor shall provide a service engineer in the customer's plant at no additional charge, for a time sufficient to install, start up the equipment, carry out the final acceptance per paragraph 7.3 and train operating personnel.

7.5 The vendor shall submit to the customer, two (2) certified copies of this machine test results prior to scheduled demonstration of these tests.

PAINT: Color required: As specified on purchase order.

The ... equipment and all associated components shall be painted with ... resistant paint, Pittsburgh No. 2376 or equivalent

WARRANTY:

Assuming the equipment is used under normal operating conditions, all repair service and required replacement parts shall be provided free of charge to General Electric Company by the vendor for a period of twelve (12) months from the date of final acceptance.

.0 SHIPPING REQUIREMENTS:

Upon acceptance for shipment, the Seller shall ship the equipment FOB receiving dock, General Electric Company, Daniel Webster Highway, Hooksett, New Hampshire.

GENERAL ELECTRIC COMPANY
Aircraft Engine Group

Installation Data

Equipment Name:

Specification No: EE-________ Rev:________

Purchase Order No:__________________________ Machine Ser No.______________

1. Shipping Weight: lbs. 1.a. Floor Space ________

2. AC Electrical Motors

| H.P. | Voltage | Amps | Phases |
|---|---|---|---|
| a. | | | |
| b. | | | |
| c. | | | |
| d. | | | |
| e. | | | |

3. D.C. Motors

| H.P. | Volts | Converter Provided |
|---|---|---|
| | | |
| | | |
| | | |

4. Other Electrical Requirements__________________________________

5. Control Panel Mounting: Attached to Machine ☐ Separate ☐
6. Special foundation required: YES ☐ NO ☐
7. Machine requires lagging: YES ☐ NO ☐
8. Leveling Accuracy required__________________________________
9. Services Required:

| | | |
|---|---|---|
| air__________ | pressure__________ | amount__________ |
| steam__________ | pressure__________ | amount__________ |
| water__________ | pressure__________ | amount__________ |
| gas (natural)__________ | pressure__________ | amount__________ |
| drain__________ | clear water__________ | special (specify)__________ |
| electric__________ | other__________ | |

Vendor:______________________________ Date______________

Signed______________________________ Phone______________

* "Yes", vendor to include descriptive information

# APPENDIX C

## SPECIFICATIONS FOR PRODUCTION INSPECTION EQUIPMENT

GENERAL ELECTRIC

A[illegible]CRAFT ENGINE GROUP

LYNN ENGINE MANUFACTURING OPERATION

Specification No HQC - 7903
Page 1 of 15
Date April 24, 1979

DESCRIPTION: INSPECTION FACILITY FOR MEASUREMENT OF T700 BLISK AND IMPELLER AIRFOILS AND FLOWPATH.

REVIEWED BY:

J. Walsh
W. Watson
M. Williams
W. Rouse
R. Yeaton
M. Gronberg
G. Levesque

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP
DANIEL WEBSTER HIGHWAY NORTH
HOOKSETT, NEW HAMPSHIRE 03106

GENERAL ELECTRIC AIRCRAFT ENGINE GROUP ENGINE MANUFACTURING OPERATION

Specification No HQC - 7903

Date April 24, 1979

DESCRIPTION: INSPECTION FACILITY FOR T700 BLISK AND IMPELLER AIRFOILS AND FLOWPATH.

PREPARED BY:

Quality Control Engineering

Mail Drop: Hooksett, Plant II

Phone: (603) 669-4900 Ext. 258

Proposed Facility Location

Satellite Plant: Hooksett

General Electric

Government X

APPROVED BY:

M. A. Gronberg
Quality Control Engineering
Mail Drop, Hooksett Plant II
Phone: (603) 669-4900 Ext. 258

APPROVED BY:

M. J. Williams
Manager, Quality Control
Mail Drop, Hooksett Plant I
Phone: (603) 669-4900 Ext. 201

GENERAL ELECTRIC COMPANY

AIRCRAFT ENGINE GROUP

DANIEL WEBSTER HIGHWAY NORTH

HOOKSETT, NEW HAMPSHIRE 03106

1.0 GENERAL

1.1 Scope: This specification covers the requirements for inspection measurement systems to provide production Quality Assurance capabilities for the Blisk and Impeller airfoil and flow path features.

1.2 Instructions for Quoting:

1.2.1 The vendor shall quote all equipment and related accessories required to meet this specification. These items must be presented in a format showing the breakdown of costs of various increments.

1.2.2 Also, quotations are encouraged for additional equipment as proposed by the vendor as an option for enhanced capability, improved time cycles or other advantages as determined by latest state-of-the-art developments.

1.2.3 The vendor's quotation must state compliance with this specification, any exceptions to this specification must be approved by the customer, therefore, exceptions must be detailed in the vendor's quotation with reference to the paragraph involved.

1.2.4 The vendor shall submit with his quotation, a completed General Electric "Data Form #DF-10" which will be considered preliminary until resubmitted in accordance with paragraph 5.1.1.

1.2.5 The vendor's quotation shall include delivery time of entire equipment package and shall be based on arrival at the designated General Electric Company Plant.

1.3 Responsibilities of the Vendor:

1.3.1 The successful vendor shall be responsible for ensuring that the equipment supplied to the customer fully complies with the requirements of this specification including any deviations accepted by the General Electric Company as referenced in paragraph 1.2.3.

1.3 Responsibilities of the Vendor: (Cont'd.)

1.3.2 The equipment described herein shall be built to customer approved drawings and/or specifications. Customer approval of any document describing a design, process, or procedure does not waive or supersede any of the requirements of this specification nor the vendors responsibility for fulfilling all of the specification requirements.

## 2.0 APPLICABLE DOCUMENTS

The following documents shall form a part of this specification. Any exceptions shall be stated in the vendor's quotation. In cases where General Electric and other codes conflict, General Electric requirements shall apply.

2.1 General Electric Specification for the Electrification of Machine Tools and Industrial Equipment No. S1231-06, dated 10-30-72. When the purchase order references a Government Contract number, the requirements for exclusive use of General Electric components, is waived.

2.2 General Electric Specification for Electronic Industrial Equipment No. S1231-07, dated 6-1-73.

2.3 General Electric Specification S1251-01, dated 5-22-75 (Electrical Grounding).

2.4 General Electric Specification S1251-20, dated 11-20-72 (Color Coding).

2.5 General Electric "Installation Data" form No. DF-10, dated 3-24-69.

2.6 National Electric Code NFPA #70 (latest edition).

2.7 The latest revision of the Joint Industrial Council's Electrical Standards for General Purpose Machine Tools.

2.8 The latest revision of the Joint Industrial Council's Hydraulic Standards.

2.9 National Machine Tool Builders Association (NMTBA) Standard.

2.10 The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section VIII.

2.11 Applicable portions of the latest edition of the U.S. Department of Labor ("Safety & Health Standards") - Title 41, Part 50-204.

3.0 SYSTEM REQUIREMENTS

3.1 This specification covers the requirements for inspection facilities to measure Blisk and Impeller airfoils and flow paths. The facility will be utilized for production measurements but must provide variable data for analytical evaluations. The design concept must be such that the inspection facility may be readily modified so as to inspect changed configurations of airfoils. The system must be a (5) axis CNC inspection machine: (4 axis under CNC simultaneous control and 1 axis mechanically adjustable for probe clearance).

3.2 Operating Condition

3.2.1 The equipment shall be located in a manufacturing environment with reasonable protection from contamination and with temperature control of ± 5° F. A maximum temperature change of 5° F /hour or 2° F in ten (10) minutes may be expected. Electrical voltage will be 110 or 220 V ± 10%, 60 cycle, single phase. Voltage fluctuations of this magnitude must not effect equipment performance.

3.2.2 Shop air will be 90 pounds per square inch gauge pressure with moisture and oil present in the air supply. Pressure controls, filters, dryers, etc. as necessary are to be provided by the vendor.

3.2.3 Vibrations from adjacent machining operations will be present and must not effect system performance. The vendor shall provide adequate controls to isolate vibrations as required.

3.3 Requirements

3.3.1 Engineering Drawings

3.3.1.1 Four different Blisks are to be inspected, but should be considered as typical only. The present engineering drawings contain many specific dimensions, requiring inspection, that are clearly defined on the drawing. However, the actual airfoil shape is defined, at present, on precision engineering masters (glass or mylar layouts) as well as basic engineering data consisting of approximately 120 points defined as "X" and "Y" coordinates for each section.

3.3.1.2 X-Y-Z coordinates with probe approach points (normal to surface) can be supplied by General Electric Company

3.3.1 Engineering Drawings (Cont'd.)

3.3.1.2 The conceptual design must be capable of accepting basic engineering data in X and Y coordinate format.

The General Electric Company will furnish this data on standard ASCII punched tape, magnetic tape or printouts as most appropriate for programming.

Software programs must be designed so as to readily accept modified or new airfoil data without major programming effort.

3.3.2 Set-up and Inspection Cycle Times

3.3.2.1 Blisk and Impeller Set-up
The system is to be designed to facilitate rapid calibration system check and part set-up for inspection. It is desireable that the changeover from one part configuration to another shall not exceed (10) ten minutes including all necessary tool changes and calibration or establishing reference datums.

3.3.2.2 Blisk and Impeller Inspection Cycle Times
Actual inspection times would be dependent on the extent of inspection required by the General Electric Company, using the full capability of the system or only partially as in a sample plan. However for evaluation of system performance the following requirements are established.

Inspection time for inspecting one (1) representative airfoil (stage 2 Blisk - all 4 inspection sections) must not exceed 25 minutes including repositioning the probe to each section. (See Exhibit I.)

The inspection time for inspecting one (1) typical full vane on the Impeller must not exceed 10 minutes, including platform. (See Exhibit II)

3.3.2 Set-up and Inspection Cycle Times (Cont'd.)

3.3.2.3 Inspection and set-up times are to be based on an "experienced, fully trained" operator.

3.3.2.4 Inspection times must include any computer time falling outside the scan cycle and time for print-out or plotting as necessary, and initial probe positioning to "zero."

3.4 Measurement fixture Datums.

3.4.1 Datums to be used for inspection operations:
The inspections are to be performed on the part usually with (but not limited to) the airfoils in the finished condition.

The curvic teeth establish both the axis and a plane datum (See Exhibit I).

Tooling and fixtures must be included to either locate these datums or stage the parts on the datums using curvic mounting rings. As an option, the General Electric Company (Hooksett) would consider grinding the curvic locating rings to fit the vendor designed tooling; necessary to position all parts.

3.5 Information Displays

3.5.1 Options: Most desireable is a means of quickly determining if the gas-path characteristics conform to drawing requirements - i.e.:

contour - convex
contour - concave
thickness
stacking axis (relative to axial and circumferential datums)
circumferential spacing
warp angle (twist)
chordal length
flow path contour (platform)

See Exhibit I

3.5 Information Displays

3.5.2 If a non-conformance situation is discovered or if variable data is necessary it is desired that a suitable means of obtaining this data be available which clearly describes the condition. Clear data output by typewriter, thermoprinter, high speed recorder or plotter is required.

3.5.3 Results of measured values printed or displayed, must be based on the English inch system and must display to four decimal places.

3.6 Human Engineering

3.6.1 All system controls and displays (electrical and mechanical) are to be located and designed for operating convenience, accessibility minimizing fatigue and error. All features requiring maintenance and adjustment are to be readily accessable with minimum mechanical interference and need for parts or assembly removals.

3.6.2 The operator should be able to remain seated throughout most of the inspection activity to avoid fatigue.

3.7 Electrical Systems

3.7.1 Electrical systems and components must be fully documented and readily maintainable with easy to use diagnostic routines. All components, major and minor, must be totally available on the domestic market.

Major peripheral components, (processors, data recorders, etc.) must be of United States manufacture and if computor capabilities are involved Digital Equipment Corporation, Hewlett Packard, and General Electric components are preferred (major maintainability consideration).

3.8 Mastering

3.8.1 Suitable calibrating techniques and masters shall be provided to check system capabilities for setups, normal usage and periodic calibrations. Masters must be easily calibrated by alternate methods which are available to the local General Electric installation.

3.9 Accuracy Requirements

3.9.1 System Accuracy - The accuracy of measurements shall be such that the probability of acceptance of nonconforming products is not significantly affected. A lack of accuracy and repeatability (including temperature effect) equal to or less than 15% of the total tolerance spread (with 95% confidence) is regarded as satisfactory for all applications. Equipment with less accuracy may not be considered without specific approval of the Purchaser's Quality Control organization.

The inspection system must perform to the above requirements for all parameters to be measured and in no case shall the capability exceed ± .0002. This accuracy must be maintained when measuring length of (20) inches on a diagonal line (corner to corner of the measuring range), (2) two sigma limit.

3.9.2 Resolution must be at least .000025.

3.9.3 Frame axes X-Y-Z must be perpendicular with each other within (1) one arc second.

3.9.4 Reference Exhibit I (Blisks) and Exhibit II (Impeller) for specific characteristic accuracy requirements.

3.9.5 Rotational accuracy for the 4th axis (rotary table)

Resolution 0.5 seconds

Accuracy ± 1 second

Face plate eccentricity (axial) ± .00016

Spindle eccentricity (radial) ± .00005

4.0 SPECIAL CONSIDERATIONS

4.1 If fastening hardware (for covers, doors, etc.) is of metric system, two (2) sets of metric tools must be provided to cover all sizes of hex socket head, hex bolt head, etc., for such hardware. The work mounting table must have tee-slots or threaded holes for hold-downs. (If threaded holes are used - they must be American Standard threads.) Any work table hold-down equipment (straps, bolts, etc.) must be American Standard Thread System.

4.2 The inspection system must be based on a (4) four axis measuring machine (CNC) with the following requirements:

4.2.1 Measuring range approximately 18" x 7" x 10" minimal,

4.2.2 X-Y-Z and 4th axis (rotating table) must have motorized drives, fully controlled and integrated into the system.

4.2.3 Joystick controls are required for X-Y-Z axis.

4.2.4 The 4th axis (rotary) must be useable in either vertical or horizontal position and be manual or computer controlled.

4.2.5 The probe head must be (3) three dimensional and must have collision protection, automatic tip pressure control, selective tip pressure and constant measuring sensitivity regardless of probe length.

4.3 Software

4.3.1 Special measurement software routines must be readily inputed as called by key or by magnetic tape cassette.

4.3.2 Software measuring programs for the Blisk and Impeller airfoils must also include the capability to mathematically best-fit airfoil sections. (2 dimensional)

4.3.3 Universal software must be available for basic configurations - available by key, including:

- spatial coordinate transformation
- ball tip correction
- recognition of axes and planes

4.3 Software (Cont'd.)

4.3.4 The system must be capable of self teaching.

4.3.5 The system must be capable of interfacing with a Honeywell H6000 via telephone for transmission of data.

## 5.0 OPERATING, INSTALLATION AND DESIGN DETAIL DOCUMENTS

5.1 As soon as the design and engineering of the equipment is completed, the vendor shall provide the customer:

5.1.1 A completed General Electric "Installation Data" form #DF-10.

5.1.2 Three (3) copies of the scaled plan view, front elevation and end elevation drawings showing location and sizes of all required services and peripheral equipment together with foundation, mounting, and interconnection details (including any optional equipment.)

5.1.3 Maintenance and service space requirements for both normal routine maintenance and major overhauls must show area necessary for auxiliary equipment (overhead crane service, fork lifts required, etc.)

5.1.4 Estimated floor weight must also be furnished at time of quotation.

5.1.5 Design layouts, tooling details, wiring and piping diagrams for customer review and approval.

5.2 At time of shipment, the vendor shall provide four (4) complete sets of reproducible electrical and piping diagrams to JIC standards as well as layout and tooling detailed drawings using format approved by General Electric.

5.3 At the time of delivery of equipment, or before final invoice is submitted, the vendor shall provide:

5.3.1 Four (4) copies of the maintenance manual and parts list and the recommended spare parts list, including preventative maintenance and lubrication instructions.

5.3 Cont'd.

5.3.2 Four (4) copies of the operating instructions.

5.3.3 Four (4) copies of the electrical, mechanical and piping diagrams.

5.3.4 In total, sufficient data must be supplied to allow complete and total maintenance of all the equipment in the customers plant. Include data to allow redesign due to major configuration changes.

5.3.5 Any warrantees, guarantees or documentation as described above for purchased components must be included and transferred to General Electric Company with the starting time of such warrantees beginning at the time the equipment is delivered to General Electric.

6.0 PROGRESS REPORTS

6.1 Within 30 days from receipt of General Electric order the vendor shall provide General Electric Company with a plan showing times and sequence of major events during the construction and testing of the equipment.

6.2 Fully explained progress reports will be supplied to General Electric Company every month until the order is 70% completed. After which, these reports shall be submitted bi-weekly until completion. In any event, the vendor shall notify the customer of any change in the schedule as soon as it occurs with appropriate explanations.

7.0 EQUIPMENT ACCEPTANCE

7.1 The vendor shall demonstrate, in his plant, that the equipment complies with the accuracy and functional requirements of this specification, under the observation of General Electric Company representative(s).

7.1.2 The test procedure shall include, but not be limited to the following:

7.1.2.1 A demonstration of all equipment and control functions, and of the equipment accuracy per Section 3.0 of this specification. (The customer has the option of requiring any or all of the tests in the procedure including the option of using his own inspection equipment.)

7.0 EQUIPMENT ACCEPTANCE (Cont'd.)

7.1.2.2 The successful processing of actual production parts as specified in Section 3.0.

7.2 Authorization to ship will be based on the successful completion of the equipment demonstrations per paragraph 7.1.

7.3 Final acceptance will be made in the customer's facility and will be based on a successful demonstration that the equipment fully meets the requirements of this specification in accordance with paragraph 7.1.2.

7.4 The vendor shall provide a service engineer in the customer's plant for a time sufficient to install, start up the equipment, carry out the final acceptance per paragraph 7.3 and train operating personnel.

7.5 The vendor shall submit to the customer, two (2) certified copies of his machine test results prior to scheduled demonstration of these tests.

8.0 PAINT

Color Required: Optional

The basic equipment and all associated components shall be painted with chemically resistant paint or equivalent. International color designation to be furnished by seller.

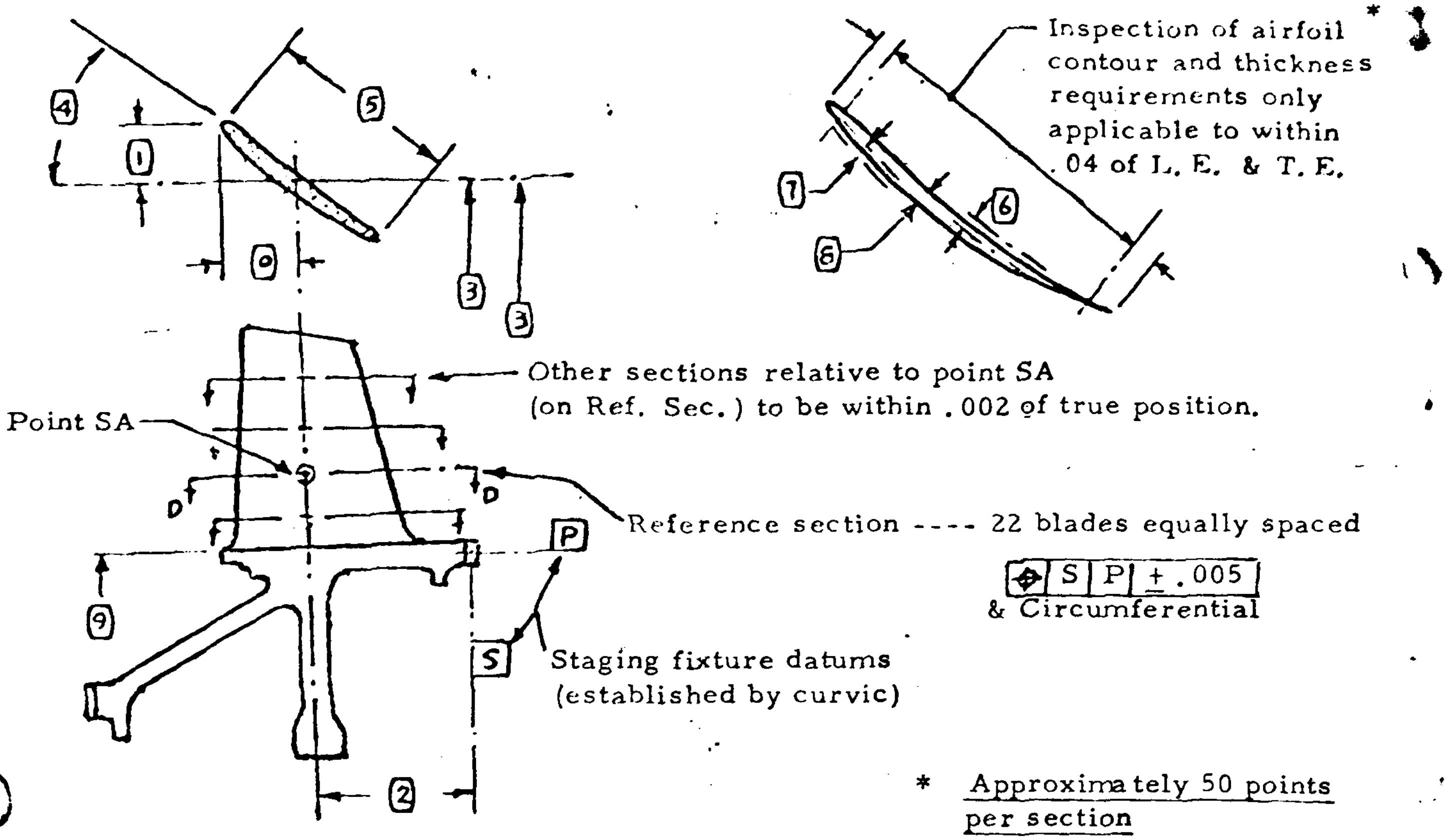
9.0 WARRANTY

Assuming the equipment is used under normal operating conditions, all repair service and required replacement parts shall be provided free of charge to General Electric Company by the vendor for a period of twelve (12) months from the date of final acceptance.

10.0 SHIPPING REQUIREMENTS

Upon acceptance for shipment, the Seller shall ship the equipment FOB receiving dock, LPM, General Electric Company, Daniel Webster Highway, Hooksett, New Hampshire 03106.

## EXHIBIT I TYPICAL AIRFOIL & PLATFORM INSPECTION REQUIREMENTS




| Characteristic | Key | Drg. Tol. |
|---|---|---|
| L. E. Tangency (Axial) | 0 | ± .004 |
| L. E. Tangency (Circumf.) | 1 | ± .004 |
| Section Pos. - Axial | 2 | ± .005 |
| Section Pos. - Circumf. | 3 | ± .002 (Rel. to Ref. Sec.) |
| Section Pos. - Circumf. | 3 | ± .005 |
| Section Pos. - Twist | 4 | ± 0° 45' |
| Chord Length | 5 | + .007<br>- .009 |
| Contour - Concave | 6 | ± .0015 |
| Contour - Convex | 7 | ± .0015 |
| Thickness | 8 | + .004<br>- .003 |
| Platform Profile | 9 | ± .004 ▲ |

▲ Average 10 points

A. For Purposes of Evaluation:

Typical Blisk - based upon Stage 2 - 6032T27

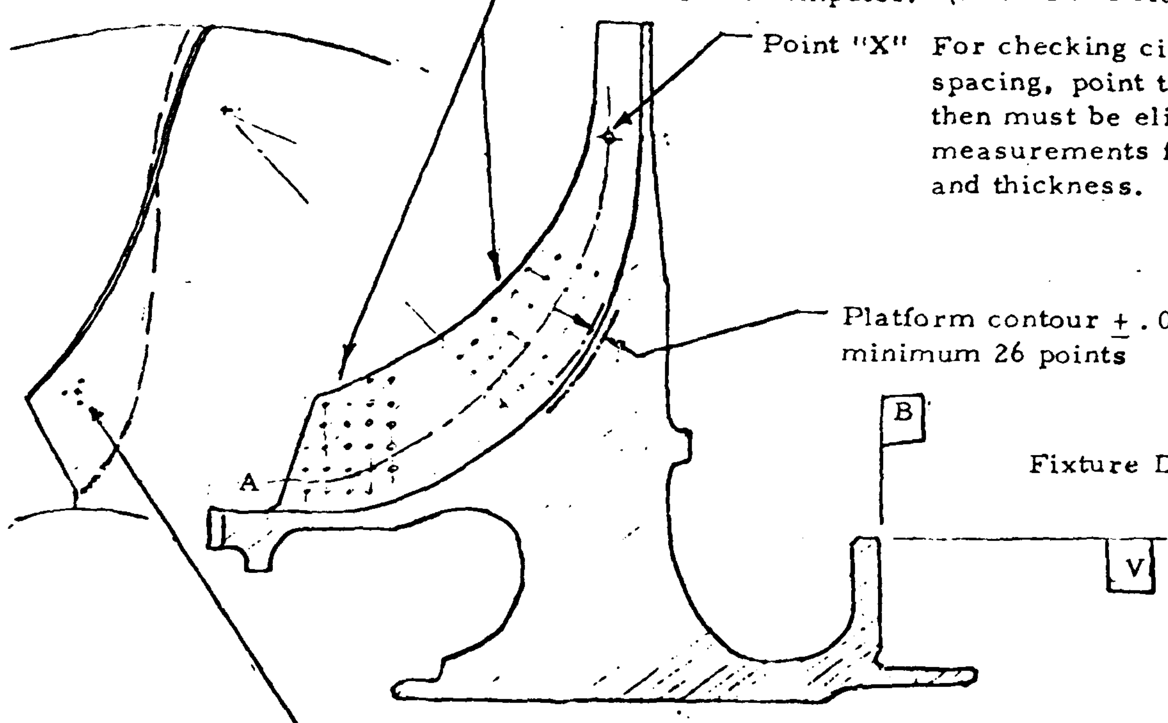
B. Inspection time requirement is based on (4) airfoil sections on (1) blade including reposition time, and curve fitting.

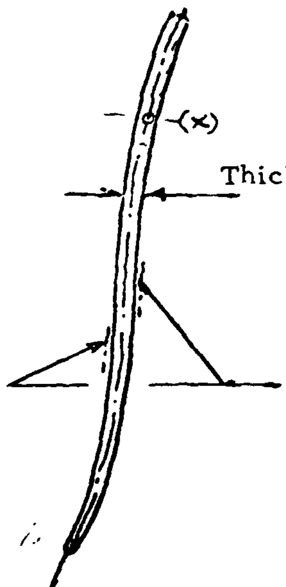
C. Peripheral length approximately 2.3 inches per section.

D. Point SA is established by the best fit of the concave and convex contours (Sec. D-D) and establishes the radial axis.

E. If additional details are required reference the engineering drawings -

| | |
|---|---|
| Stage 1 | 6032T26 |
| Stage 2 | 6032T27 |
| Stage 3/4 | 6038T08 |
| Stage 5 | 6038T09 |




1. It is desirable to have output information in the form of a 2 dimensional graph of a 3 dimensions surface, with a printout of deviations of X, Y and Z

A. For purpose of evaluation:

   Inspection time should be based upon; inspecting (1) full airfoil for contour and thickness, approximetely (50) points. May be a grid pattern using a cartesian or polar coordinate system.

B. If additional information is required reference the engineering drawing 6038T74.

GENERAL ELECTRIC

AIRCRAFT ENGINE GROUP

LYNN ENGINE MANUFACTURING OPERATION

SE131b-A

QUALITY INFORMATION

Specification No 4-77-1

Page 1 of 6

Date 4/27/77

Description:

Leading Edge, Light Sectioning Inspection System
T700 Blisk & Impellar

Prepared By: R. J. LeJeune 4/27/77
Advanced Quality Control Engineering
Mail 26803 Phone: (617) 594-5789

Approved By: ______ Reviewed by: 5/3/77

GENERAL ELECTRIC COMPANY

AIRCRAFT ENGINE GROUP

1000 WESTERN AVE. - LYNN - MASSACHUSETTS 01910

AD-A093 877 GENERAL ELECTRIC CO LYNN MA AIRCRAFT ENGINE GROUP F/G 13/8
T700 BLISK AND IMPELLER MANUFACTURING PROCESS DFVELOPMENT PROGR--ETC(U)
NOV 79 W A HUNTER, G A GRIMMER DAAJ01-75-C-0844
UNCLASSIFIED R80AEG035 USAAVRADCOM-TR-80-F-1 NL

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SE131b-A

## 1.0 GENERAL

### 1.1 Scope

This specification describes the basic requirements for a System which will inspect Jet Engine "Blisks" and "Impellars" for leading edge contour to the limits defined on General Electric Engineering Drawings and Specifications listed in Para. 2.0.

### 1.2 Instructions for Quoting

1.2.1 The vendor's quotation must state complience with this specification. Some exceptions may be approved by the customer, therefore, exceptions must be detailed in the vendor's quote with Ref. to the paragraph involved.

1.2.2 The vendor's quotation must include delivery time of entire equipment package.

1.2.3 The vendor's quotation shall include a separate price for the additional features described in Para. 7.0.

### 1.3 Responsibilities of the Vendor

1.3.1 The successful vendor shall be responsible for ensuring that the equipment supplied to the customer fully complies with the requirements of this specification including any deviations accepted by the customer.

1.3.2 The equipment described herein shall be built to customer approved drawings. Customer approval of any document describing a design, process or procedure does not waive or supercede any of the requirements of this specification nor the vendor's responsibility for fulfilling all of the specification requirements.

## 2.0 APPLICABLE DOCUMENTS

The following General Electric Co. Drawings and Specifications define the parts which will be inspected with the equipment specified herein, and the acceptance limits for these parts. These drawings are proprietary to General Electric Co. to the extent as follows:

PROPRIETARY INFORMATION

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2.0 APPLICABLE DOCUMENTS (Cont'd)

| DOCUMENT NO. | DESCRIPTION |
|---|---|
| 6032T26 | Stage 1 Blade & Disk (Blisk) |
| 6032T27 | Stage 2 Blade & Disk (Blisk) |
| 6038T08 | Stage 3 & 4 Blade & Disk (Blisk) |
| 6038T09 | Stage 5 Blade & Disk (Blisk) |
| M50TF2213 | Acceptability Limits for Integral Blade/Disk Airfoils |
| 6038T74 | Impellar |

3.0 SYSTEM REQUIREMENTS

3.1 The equipment specified herein shall be used for optical inspection of airfoil leading edge contour, utilizing light sectioning, positioned at the point where the inspection sections, defined on the engineering drawings (Para. 2.0), pass thru the leading edge.

3.2 The equipment will be used in production inspection and must be engineered for ease of operation by inspection personnel. Set-ups are to be made as simple as possible.

3.3 Optical System

3.3.1 The system shall include high quality optics suitable for TV and photographic image transfer. Lenses for 20X and 40X magnification shall be provided by the vendor.

3.3.2 The microscope shall be equipped with two viewing ports. One shall be adaptable for photographic and/or TV camera and the other shall provide direct viewing by the operator and shall be positioned for optimum viewing comfort.

3.3.3 A system shall be built-in which will project a retical image onto the field of view. The retical projection device shall have a turret device which will contain no less than (6) reticles for selective projection.

3.3.4 The retical projection system shall be rigidly mounted and shall have all necessary adjustments to focus and orient the image to the optical field. All adjustments shall lock in place.

3.3.5 Reticals, mounted in suitable holders, shall be provided by the customer at time of equipment acceptance at the vendors plant.

3.4 Illuminator System

3.4.1 A collimated, horizontal, single beam of high intensity light shall be provided at a fixed focal distance 90° to the optical centerline. The beam width shall be sufficient enough to extend at least 1/8 inch on either side

3.4 Illuminator System - Cont'd

of the leading edge.

3.4.2 The light source shall be either laser or an adjustable high intensity lamp using fibre optic bundles from a single power supply.

3.4.3 The illuminator support shall be mounted vertically behind the microscope and may require an extendable tube which will direct the light beam 90° to the optical axis, the tube shall be small enough to position between rows of blades on stage 3 & 4 Blisk and Impellar.

3.4.4 The illuminator support must be of rigid design set at a fixed focal distance from the optics. Fine adjustment for focus shall be provided in the event the focus becomes disturbed. These adjustments shall be firmly lockable and not exposed to manipulation by operating personnel.

3.5 PART POSITIONING

3.5.1 The microscope, reticle and illuminator system shall be integrated into a floor mounted fixturing device, which shall position each part specified in Para. 2.0 such that the intent of the engineering drawing, with respect to leading edge inspection, is met.

3.5.2 The basic fixturing device shall consist of an elevated staging table, horizontal rotating plate or equiv. for twist adjustment, transverse and lateral slides for positioning the part in the optical field, and rotating part holders (arbors) for orienting the leading edge to the vertical optical axis.

3.5.3 Elevated Table shall consist of a precision vertical slide, manually operated, to position the part to the correct "radial" height. The vertical position will be determined by a digital readout with a scale and read head and shall be located in a convenient position for operator viewing. A fine adjustment and locking feature shall be provided.

3.5.4 Mechanically calibrated masters shall be provided by the vendor, for each part in Para. 2.0, to verify that the optical section is in the correct radial position.

3.5.5 The horizontal, rotating plate shall have markings identifying positions by part ident. for ease of set-up, and shall lock into position. The center of rotation shall be in line with the optical center.

3.5.6 Transverse and lateral cross-slides shall incorporate fine adjustments with appropriate scale markings for repeating set-up. These slides shall have convenient locking devices.

3.5 PART POSITIONING (Cont'd)

3.5.7 The part holder shall be attached to the transverse slide and shall include :

3.5.7.1 Part holding arbors with convenient clamping device shall be staged horizontally on a suitable support member permanently attached to the transverse slide.

3.5.7.2 Part locating datums, based on finish part size, will be provided by the customer at time of order.

3.5.7.3 A simple and effective means of orienting the rotational position of each blade on the arbor for each part in Para. 2.0 shall be provided. This device shall consistantly position the leading edges of each part, in line with the optical axis, within ±.0005 inches to two (2) SIGMA limits or better, measured at any point on the leading edge profile.

3.5.8 A tilting mechanism will be required to present the impeller leading edge normal to the optical axis and shall have fixed stops as required for proper tilt angle.

3.6 EQUIPMENT ACCURACY AND REPEATABILITY

3.6.1 The equipment covered by this specification must be capable of inspecting leading edge contour in accordance with M50TF2213, Para. 3.1.8.2.

3.6.2 The vertical slide with digital readout shall have a positioning and repeatability accuracy of ±.001 inches within (2) sigma limits, or better. (Also ref. Para. 3.5.7.3)

3.6.3 The resolution of the digital readout shall be to .001 inches or better.

4.0 OPERATING & CALIBRATION INSTRUCTIONS shall be provided by the vendor at time of equipment acceptance at his plant.

5.0 EQUIPMENT ACCEPTANCE

5.1 The vendor shall demonstrate in his plant and after installation in the customer's plant, that the equipment complies with all of the accuracy and functional requirements of this specification, under the observation of General Electric Co. Representative(s).

5.1.1 The demonstration shall include, but not be limited to the successful processing of sample production parts.

5.1.2 Final acceptance will be in the customer's plant in accordance with Para. 5.1.

6.0 WARRANTY

Assuming the equipment is used under normal operating conditions, all repair service and required replacement parts shall be provided free of charge to General Electric Co. by the vendor, for a period of twelve (12) months from the date of final acceptance.

7.0 ADDITIONAL FEATURES

Each of the following features is to be quoted separately.

7.1 One closed circuit TV camera + monitor including any adaptors required to mount to the equipment per Para. 3.3.2.

7.2 One Polaroid camera ADAPTOR. (Ref. Para. 3.3.2)

7.3 Dual Illuminators mounted on single adaptor bracket instead of single illuminator per Para. 3.4, but with similar features.

DF-10

GENERAL ELECTRIC COMPANY

Aircraft Engine Group

Installation Data

Equipment Name:

Specification No: [redacted]- HQC-1903 Rev:_______

Purchase Order No:______________________ Machine Ser No.__________

1. Shipping Weight: lbs. 1.a. Floor Space Req.___

2. AC Electrical Motors

| | H.P. | Voltage | Amps | Phase |
|---|---|---|---|---|
| a. | | | | |
| b. | | | | |
| c. | | | | |
| d. | | | | |
| e. | | | | |

3. D.C. Motors

| H.P. | Volts | Converter Provided |
|---|---|---|
| | | |
| | | |
| | | |

4. Other Electrical Requirements______________________________

5. Control Panel Mounting: Attached to Machine ☐ Separate ☐

*6. Special foundation required: YES ☐ NO ☐

*7. Machine requires lagging: YES ☐ NO ☐

8. Leveling Accuracy required______________________________

9. Services Required:

| | | |
|---|---|---|
| air______________ | pressure__________ | amount______________ |
| steam____________ | pressure__________ | amount______________ |
| water____________ | pressure__________ | amount______________ |
| gas (natural)______ | pressure__________ | amount______________ |
| drain____________ | clear water_______ | special (specify)______ |
| electric__________ | other______________ | |

Vendor:______________________________________ Date__________

Signed______________________________________ Phone_________

*If "Yes", vendor to include descriptive information.

DATE
ILMED
-8